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REPORT ON ANNUAL HIGHWAY COSTS

PROVINCE OF ONTARIO

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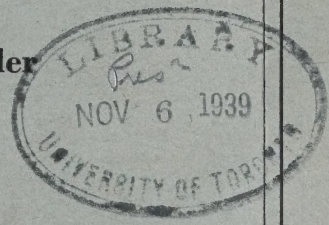
The Railway Association of Canada

- by -

C. B. Breed, Clifford Older

and

Wm. S. Downs



February 21, 1938

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Report on

The Annual Cost of

Constructing, Maintaining and Administering

Public Roads in the Province of Ontario,

The Portion of Such Costs which Should be Paid by

The Owners of Motor Vehicles

and the

Allocation of Such Portion among

Different Classes of Motor Vehicles

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February 21, 1938



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TABLE OF CONTENTS

Page No.

Letter of Transmittal	1
Foreword	2
Scope of Report	4
Summary of Procedure	7
Total Annual Highway Expenditure - Before 1919	11
Rural Road Expenditures - 1890 to 1936	14
Urban Street Expenditures - 1890 to 1936	18
Elements of Annual Highway Cost - After 1918	20
Amortization	20
Interest	20
Property Taxes	20
Maintenance	21
Computation of Annual Cost of Rural Roads - After 1918	24
Computation of Annual Cost of Urban Streets - After 1918	28
Combined Annual Cost of Roads and Streets Compared with Motor Vehicle Revenue - After 1918	31
Subsidy, or Highway Debt, also Charged to the General Public	33
Discussion of the Effect of Service Life and Salvage Value upon Annual Costs	38
Total Annual Road Costs - Portion Charged for Social- Necessity Uses	42
Allocation of Annual Road Costs - Discussion of Methods of Allocation to Different Types of Motor Vehicles	42
I. Allocating annual highway costs on the basis of vehicle miles	42
II. Allocating annual highway costs on the basis of occupancy of the highway	43
III. Speed ton-mile allocation	43
IV. The Increment Method	46
V. Straight Ton-Mile Method	46
VI. Combined Increment and Ton-Mile Method	46

TABLE OF CONTENTS (continued)Page No.

SQUARE ROOT OF WHEEL LOAD BASIS FOR ALLOCATION

General Relation between Wheel Load and Thickness of Pavement	48
Square Root Relation - Cement Concrete Pavements . . .	52
Square Root Relation - Bituminous Pavements	60
Square Root Relation in Design Formula for Flexible Types	63
Square Root Rule - Gravel and Earth Roads	65
Does Annual Cost Vary as Square Root of Wheel Load? . .	66
Application of the Square Root Method of Allocation of Costs between Classes of Motor Vehicles	72
Straight Ton-Mile Basis for Allocation of Costs	81
Combined Square Root and Ton-Mile Method of Allocation	83
Ton-Mile Basis with Increasing Ton-Mile Basis	89
Other Elements of Highway Cost Incurred for the Heavier Commercial Vehicles - Advantages Enjoyed by the Trucks - Delays and Hazards They Cause	94
Additional Width of Pavements and Shoulders . .	96
Additional Lanes	102
Additional Maintenance of Road Surfaces and Shoulders	104
Shortened Life of Pavements	104
Nuisance, Delays and Hazards to Other Traffic .	105
Special Benefits to Heavier Vehicles from Road Improvements and Grade Reduction	112
Relative Road Occupancy of Trucks and Passenger Cars	115
Use of the Highways as a Place of Business . .	119
Summary	120
APPENDIX A	
APPENDIX B	

February 21, 1938

Mr. C. P. Riddell, General Secretary
Railway Association of Canada
437 St. James Street
Montreal, P. Q.

Dear Sir:

Complying with your instructions, we have
made a study and Report on Cost of Ontario Highways and
Allocation of Highway Costs.

This report is submitted herewith.

Yours truly,

C. B. Reed
Clifford Alder
A. H. Rogers
Consulting Engineers

FOREWORD

This study has been undertaken for the purpose of determining a sound basis for applying the general principle that the motor vehicle should pay its fair share of the cost of highways and streets.

A comparison of the annual cost of highways and streets in Ontario with the revenues collected from motor vehicles will reveal the extent, if any, to which the road users as a class are subsidized. Allocation of these costs to different classifications of vehicles when compared with present fees will show the extent to which each class pays or does not pay its fair share of rural highway and street costs.

Several methods of approach to this problem have been developed and used in other studies of a similar character. Many of these studies will be found in published reports. After having given consideration to all of these methods, we have adopted a method of analysis which we believe to be equitable, and have applied it to the Ontario problem.

Scope of Report

The analysis of annual highway costs and their allocation naturally falls into three recognized divisions, viz.,

- (1) the determination of the annual cost
- (2) the division of the annual cost between the general public and the motor vehicle owner
- (3) the allocation of the motor vehicle portion between the different types of motor vehicles.

(1) The determination of the total annual cost of all rural and urban highways should include the annual amortization of capital costs, interest and taxes on unamortized capital, annual maintenance and operation (including administration).

As soon as a highway is built, it begins to wear out, therefore a portion of the capital cost must be retired each year, i.e., amortized. The remaining capital investment, the unamortized cost, is the amount upon which interest and taxes are charged.

(2) The divisions of the total annual cost between the general public and the motor vehicle is based on the relative requirements for social-necessity and the requirements for motor vehicle use.

(3) If all types of vehicles required the same annual highway cost per vehicle and made the same use of the roads, then the total annual cost chargeable to those users could properly be allocated equally to every motor vehicle. But since some types of vehicles require greater annual highway costs than others due to their heavier loads, more frequent use, greater width and other special highway requirements, then those vehicles which cause a greater annual road cost should pay a correspondingly greater charge, i.e., they should produce a greater revenue per vehicle.

The allocation between types of vehicles involves therefore a study of two major items, namely, the highway FACILITIES REQUIRED and the USE MADE of the roads. In this report charges for the facilities required are made in proportion to the square root of the wheel load, upon what is sometimes called the "increment" basis. Charges for use have been determined on a ton-mile basis or a modification of it.

Summary of Procedure

After an exhaustive study of this problem, the following simple method of analysis has been adopted. Later in this report the reasons supporting this method will be given as well as the reasons for not adopting methods heretofore proposed in other similar studies.

The method proposed is a simple exposition of a complicated problem. It embodies the basic economic elements of highway costs; it disposes of many of the controversial features which always have complicated such problems; it is easy to apply; and in our opinion it is equitable.

No charge is made to the motor vehicle user for the roads and streets, including the value of rights-of-way, as they existed December 31, 1918. This act together with the exclusion of the cost of street sidewalks and lighting constitutes in our opinion payment in full by the general public for social-necessity use of roads. Beginning January 1, 1919, the motor vehicle user is charged with all the annual cost of rural roads and of urban streets (except sidewalks and street lighting); but the vehicle owner is not charged for the unamortized capital cost incurred prior to that date.

The above expresses our view as to full compensation for so-called social-necessity use. The revenue

from January 1, 1919 to March 31, 1937, however, failed to meet the annual highway costs by \$326,000,000. This accumulated deficit was incurred wholly on account of facilities required for the motor vehicle, and consequently it was and still is their obligation to pay this debt, but since it has been permitted to accumulate to such an extensive amount, repayment would now impose a charge against the motor vehicle owner that is practically prohibitive. It is probably impracticable, if not unfair, to expect motor vehicle users in the future to pay such a deficit accumulated by motor vehicle users in the past. The only fair way we can see of disposing of this debt is to treat it as an error of the past and charge it to the public.

In this study, therefore, the motor vehicle owners are not charged with (a) the investment in right-of-way, (b) the annual cost of all roads built prior to 1919, (c) the total deficit accumulated from 1919 to 1936, and (d) lighting and sidewalks for urban streets. These charges are assigned in full to the general public, and constitute its full payment for social-necessity use of roads. From 1936 on, i.e., from the present time on, motor vehicle owners should assume full responsibility for all annual costs of rural roads and urban streets. This is in accordance with the principle set forth in the Salter Report (Report of the Conference on Rail and

Road Transport, Great Britain).

Allocation of highway charges as between different classes of motor vehicles has been made first on the basis of FACILITIES REQUIRED by the different classes, and then within each class the allocation has been made on the basis of USE MADE, measured in ton-miles. Secondly, a ton-mile basis has been developed with a greater rate per ton-mile charged to the heavier commercial vehicles than to the lighter ones, thus charging for both facilities and use in ton-mile units.

Total Annual Highway Expenditure - Before 1919

During the 30 years previous to 1919, not less than \$54,000,000 was expended on construction of rural roads. Even though capital expenditures were partly depleted through wear, yet considerable portions of the road elements purchased before 1919 still remained in 1919; the entire right-of-way, and a very considerable value in the bridges and pavements still remained. All these values we have treated as "heritage from the past" in payment for social-necessity use and have therefore assigned to rural roads no unamortized value as of December 31, 1918 although it was at least \$30,000,000 in addition to rights-of-way. Similarly, the value of all municipal streets on which many millions of dollars had been expended prior to 1919 (\$38,000,000 for construction from 1900 to 1919) have also been treated as "heritage from the past". Thus, the motor vehicle users are relieved from paying interest on the value of the right-of-way and on construction expenditures and from payments for amortization of the capital expended on rural roads or city streets before 1919.

Fig. 1 is a graphical representation of the annual expenditures on rural roads from 1890 to 1918 and on city streets from 1900 to 1918. The expenditures on city streets are plotted above the expenditures on rural roads; the top line therefore indicates total

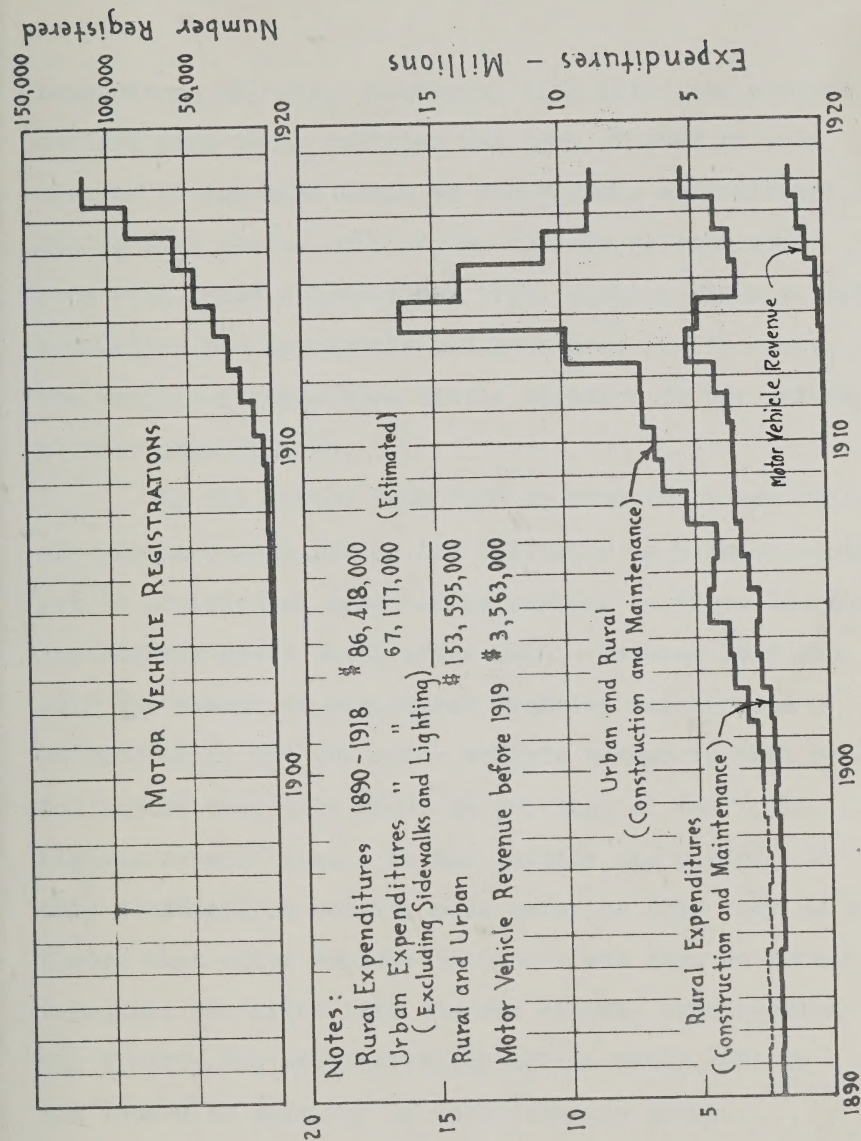


Fig. 1

EXPENDITURES FOR RURAL ROADS AND URBAN STREETS - PROVINCE OF ONTARIO
 COMPARED WITH MOTOR VEHICLE REVENUE — 1890 - 1918 INCL.

expenditure on both. Beginning with 1910, the revenue derived from motor vehicles has been plotted on this diagram to the same scale as the highway expenditures. During that period most of the vehicle revenue came from city owned automobiles. Fig. 1 shows clearly that even after the automobile had been here for 10 years, the vehicle revenue bore little relation to the annual highway expenditures.

In the period from 1900 to 1910 the motor vehicle was certainly having its influence on highway costs, yet it contributed practically nothing to these increasing highway costs until after 1910. Between 1910 and 1919 the number of registered vehicles reached the 100,000 mark; yet the motor vehicle owners in that period contributed only about $3\frac{1}{2}$ per cent of the total highway expenditures. We can justify the payment of this considerable subsidy made prior to 1919 only on the theory that motor vehicle transport was then an infant industry; but after 1918 the new highway construction was clearly the responsibility of the motor vehicle and should be paid for by motor vehicle users.

The motor vehicle registration is plotted in the upper portion of Fig. 1. Reading this diagram as a whole, it will be noticed that as the registration rapidly increased, highway expenses also shot up until the war (1914), but motor vehicle revenue (plotted at the bottom

of the sheet) did not keep pace at all with the rapid increase in expenditures. The rapid growth in motor vehicle use obviously called for larger expenditures, but it was not until after 1918 that the Province began to collect these added costs in any appreciable amount from motor vehicle revenues. The public apparently were not at first aware of the tremendous increase that the motor vehicles were destined to cause in road costs. The war came in 1914 and the resulting necessary economies in all public expenditures completely masked the effect that the motor vehicle was having upon highway costs. This was to be reflected in the large highway expenditures of the years immediately after the war.

Rural Road Expenditures 1890 to 1936

A graphical representation of the annual expenditures on rural roads from 1890 to 1936 is shown in Fig. 2. The amounts shown include expenditures for all King's Highways, County and Township roads. It will be noticed that from 1890 until 1902 the total annual expenditure was about \$2,000,000, and that from 1902 on until 1913 there was an increase to about \$5,000,000. Then came the four war years which affected highway expenditures as well as everything else; these cannot be considered as representative years. In 1919 the annual expenditure jumped to \$12,000,000 and continued to increase. From 1903 on to 1918 the motor vehicle was beginning to have some influence on highway requirements. In fact, there was a start toward increased annual expenditures around the year 1913-14, which, viewed in the present light, appeared to be a "false start" because the war stopped everything. During the war period the motor vehicle was building up a demand for improvements which, in stress of conflict, could not be met. This lag in meeting these requirements resulted in a tremendous increase in expenditure for the years 1919 to 1921, which is vividly pictured in the diagram.

Fig. 2 shows a slowing up in expenditures from 1924 to 1926 and then another upward spurt until 1930

EXPENDITURES FOR RURAL ROADS. (CONSTRUCTION AND MAINTENANCE) - PROVINCE OF ONTARIO - 1890-1936

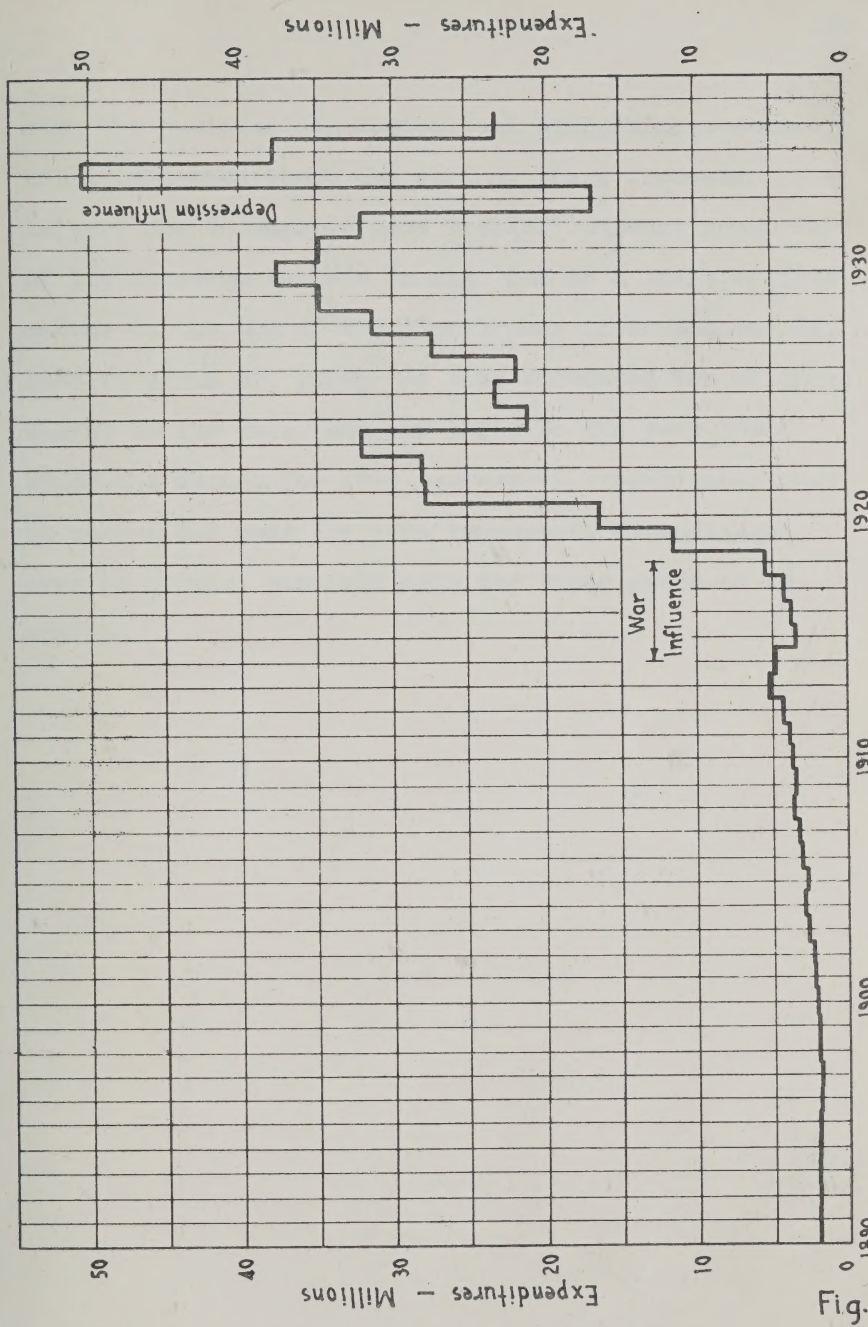


Fig. 2

when the business depression sent everything downward until 1934 when there was another sharp increase largely due to unemployment "relief" expenditures. Part of the increase in 1934 is also due to a shift of five months in the end of the fiscal year (from October 31, 1934 to March 31, 1935); we have allocated two of these months to the year 1934 and three to the year 1935; hence the amount for 1934 represents expenditures over 14 months and that for 1935 represents expenditures over 15 months, compared with the other years of 12 months.

Urban Street Expenditures - 1890 to 1936

The annual expenditures for city streets in Ontario are shown graphically in Fig. 3. Since complete records of expenditures for all cities and towns were not available for the period covered in this chart, the amounts had to be estimated based upon the complete statistics available for a representative group of municipalities. Complete expenditures were assembled for the following places which include about 45% of the total urban population: Toronto, Hamilton, London, Kingston, Guelph, Belleville, Stratford, Barrie and Lindsay. The sum of the expenditures for these selected municipalities was expanded in proportion to population to represent all urban street expenditures. Items for sidewalks and lighting were excluded, as these costs were incurred for the general public rather than for motor vehicle use.

Fig. 3 shows that expenditures ran rather uniform in amount until 1904. Then there was a gradual increase from 1904 to 1912, during which period the motor vehicle was certainly having an effect on the cost of city streets. This effect was vividly shown in the prosperous years, 1912-14; then came the war which curtailed all expenditures. From 1918 there was a large increase until the years 1925-27 when there was a falling off similar to that in rural road expenditures. After that, expenditures again increased rapidly until the business depression began to affect expenditures; but probably on

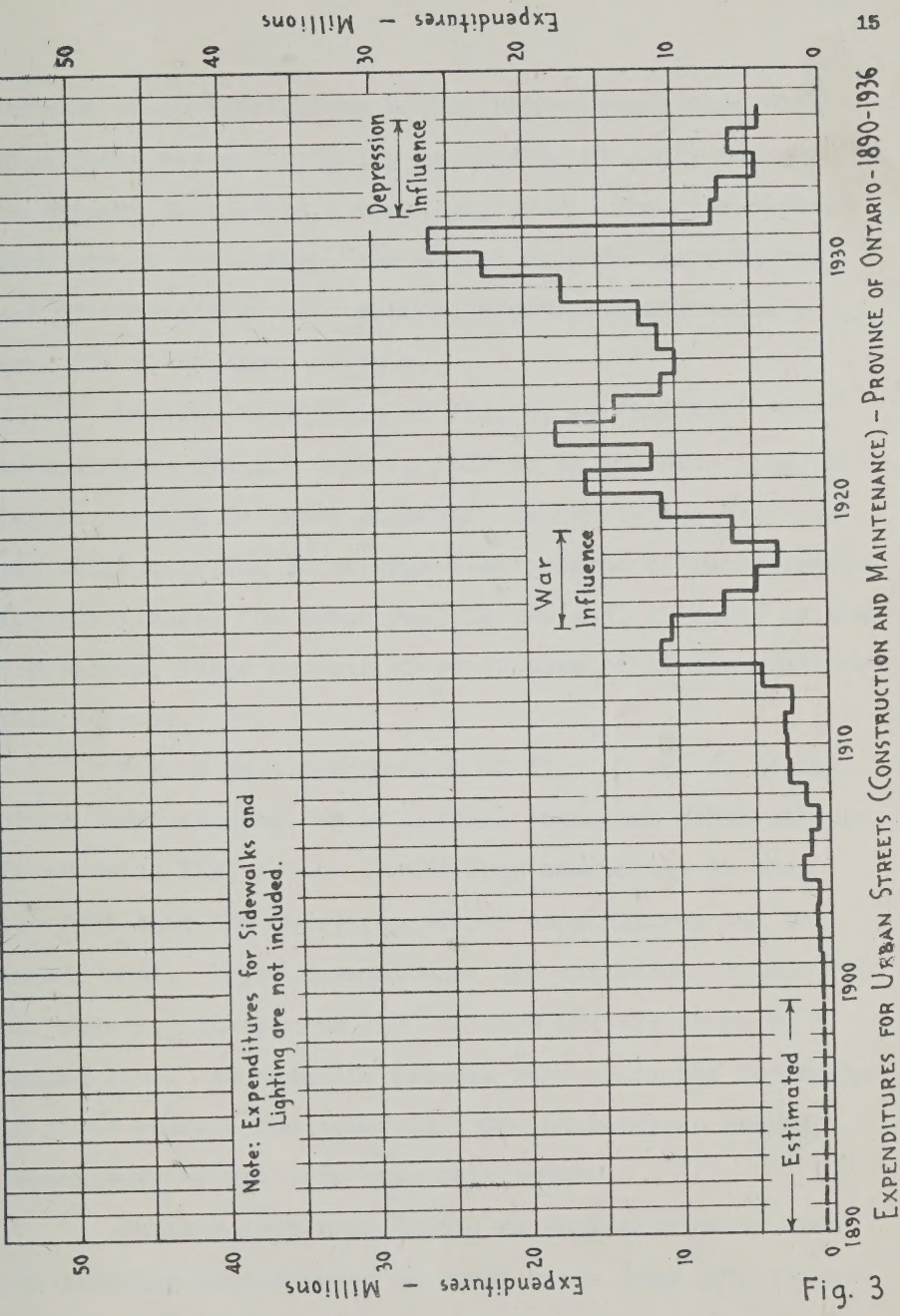


Fig. 3

account of appropriations having been already made the high point was not actually reached until 1931; then expenditures dropped to a very low level. When the depression struck the cities, the amount expended represented not much more than maintenance, capital expenditures were cut to the bare minimum.

Looking back again at Fig. 2, we find that rural expenditures did not drop in 1935-36 to anything like the levels reached by urban streets. Evidently the Province was still carrying on an expansion program of reconstructing rural roads for motor vehicle use and, in spite of the depression, large amounts of money were still expended for this purpose.

Fig. 4 is a combination of Figs. 2 and 3; it includes expenditures for both rural roads and urban streets. In studying Fig. 4, one should keep constantly in mind the fact that the chart represents expenditures and not annual cost. Urban expenditures are estimated at \$500,000 per year for the period 1890 to 1899 and are shown by a dashed line. No adequate records were available for costs in these years. The trend in 1900 indicates an annual expenditure of not less than this amount.

Another fact that should be kept in mind is that considerable expenditures on rural roads from 1900-10 was rather costly because it was largely statute labor, and the further fact that the same work could be done today for a much less cost.

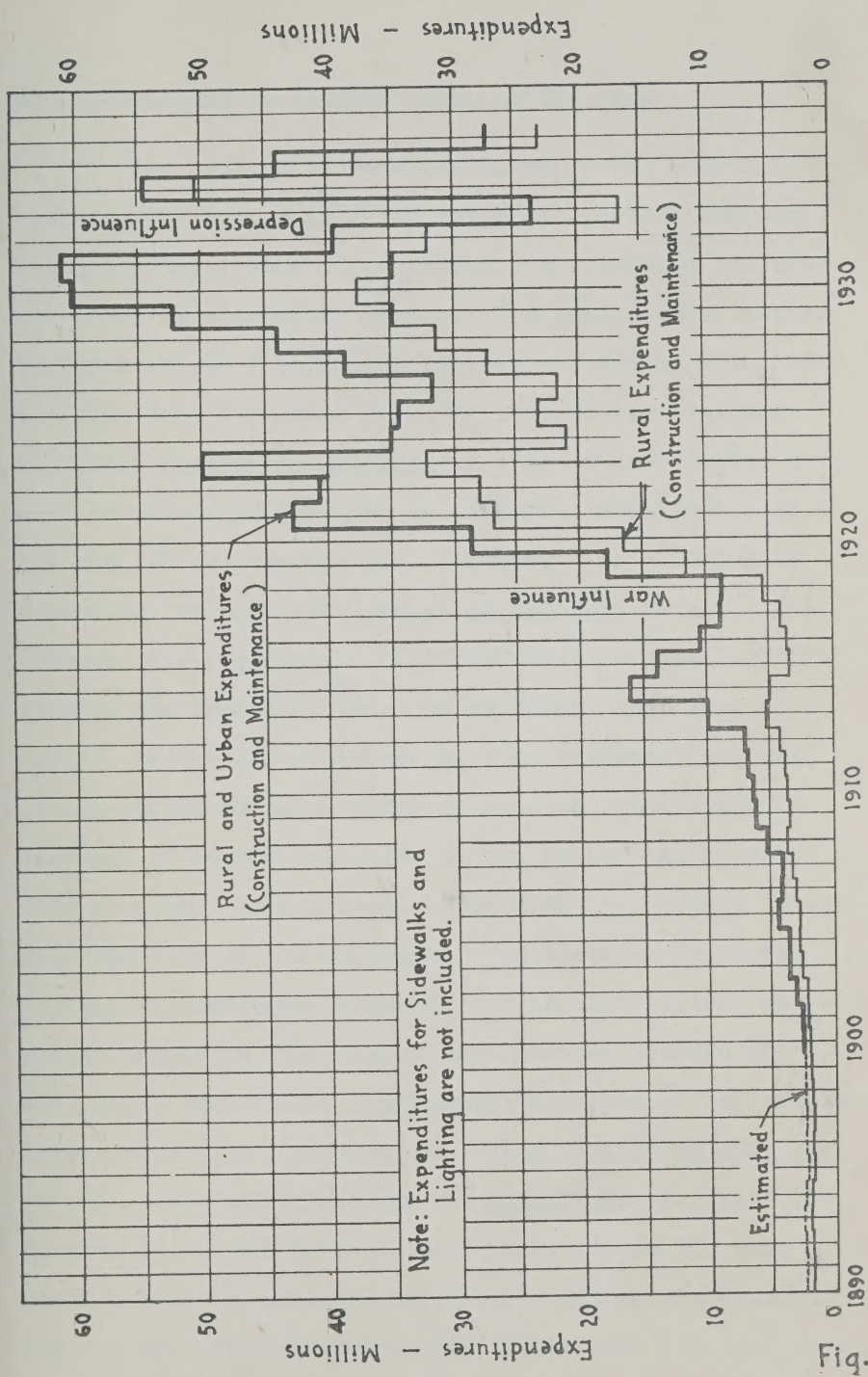


Fig. 4

Elements of Annual Highway Cost - After 1918

The problem of determining the total annual road cost for the period in which the motor vehicle has been the governing factor (from December 31, 1918 to the present time) is reasonably simple. The period under review includes 18 years beginning in 1919 and ending with 1936, the last year for which complete records are available. The total annual expenditures in this 18-year period have been compiled and they can be separated between (1) capital and (2) maintenance and operating. In a period of expansion, as this was, annual expenditure is not a fair measure of annual cost. The fundamental reason for this lies in the fact that those expenditures that were of a capital nature largely produced road elements (grading, pavements and bridges) which as soon as built begin to wear out or become obsolete; at the end of their useful life they must be replaced. Consequently, we must investigate the life of the different road elements which the capital expenditures purchased during that period, and a proper amount of the cost of them must be charged off each year; this amount represents the value of the yearly deterioration or obsolescence. Thus capital expenditure, as such, does not appear in the annual cost but only the portion to be amortized in that year. Since the only portion that is deteriorated (or has become obsolete) in any one year is included in the annual cost for that year,

the unamortized portion remains to be carried as an investment. It is, therefore, proper to include interest on the unamortized portion of the road elements as part of the annual cost.

Total Annual Highway Costs should, therefore, be made up of the following elements:-

(a) Annual charge to amortize capital expenditures over the period of life of the road elements which the capital expenditure purchased.

(b) Interest and taxes on unamortized portion of the road elements which the capital expenditure purchased.

(c) Annual maintenance, including operating cost, administration, policing, etc.

The annual cost of rural highways has been determined separate from the annual cost of urban streets.

In this report the compilation of annual costs is based upon construction and maintenance costs obtained from the records of the Ontario Department of Highways in the case of rural roads and from the expansion of costs for selected municipalities in the case of urban streets. Since complete cost data are not available for all urban places, it was necessary to expand the costs obtained for the selected municipalities on a population basis in order to obtain representative costs for all urban streets.

Amortization.

The construction expenditures (capital costs) are completely amortized over a period of 25 years, which is estimated to be the average service life of the highway elements purchased by this capital. Whatever salvage value these elements may have at the end of this period is given to posterity. This method of procedure is fully explained later in the report.

Interest.

The rate of interest adopted in the report is 4.55%. It was determined by finding the weighted average of the interest rates which the provincial public debt carried in the issues of 1919 to 1936 inclusive.

Property Taxes.

In determining the proper amount to be charged for the use of highways and streets, it is sound economics to include an item of property tax on the highway valuation. Taxes, like interest charges, may be properly included as an element of cost. Property taxes are included at the rate of 1%; this being the comparable rate of taxation that the railroads pay on their properties. It is an appropriate charge to annual expenditures because practically all vehicles which use the highways are doing so in competition with other transportation agencies which have to pay taxes.

Maintenance

Annual maintenance costs include administration, superintendence, policing and snow removal as well as the usual items of annual road repair and up-keep.

Computation of Annual Costs of Rural Roads - After 1918

The computation of the annual costs for rural roads is shown in Table I, and the resulting annual costs are plotted in Fig. 5. The computations for the years 1919 to 1936 are based upon recorded construction and maintenance costs using the procedure outlined above. They are extended from 1937 to 1945 upon the assumptions that maintenance costs in 1937 will be equal to the average for the preceding 10 years, and will increase thereafter at the rate of 4 per cent per year, which corresponds to the present trend in motor vehicle registrations.

In Fig. 5, annual expenditures are shown year by year from 1890 through to 1918 by the dotted line at the left of the diagram. The heavy full line, beginning in the year 1919, represents the annual cost of all rural highways year by year. It will be noticed that there is a rapid increase in annual costs from 1918 to 1930, then for 4 years there was practically no increase in annual costs due to retrenchments in expenditures on account of the business depression. In 1935 there was a large increase in annual expenditure in an attempt to make up for deferred construction and maintenance in the previous period, coupled with the necessity for "unemployment relief".

TABLE I
COMPUTATION OF ANNUAL COSTS FOR RURAL ROADS
PROVINCE OF ONTARIO - 1919-1945

Year	Construction Expenditures	Amortization Charges for Each Year's Construction (2) ÷ 25	Current Year's Amortization Charges	Unamortized Construction Cost at the Beginning of Each Year	Interest on Unamortized Construction Cost 4.55% of (5)	Taxes on Unamortized Construction Cost 1% of (5)	Maintenance Expenditures	Total Annual Cost of Rural Roads (4)+(5)+(7)+(8)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1919	\$7,941,000	\$ 317,000	\$ --	\$ --	\$ --	\$ --	\$3,624,000	\$ 3,624,000
1920	12,261,000	490,000	317,000	7,941,000	361,000	79,000	4,188,000	4,945,000
1921	20,295,000	812,000	807,000	19,885,000	905,000	199,000	7,510,000	9,421,000
1922	20,586,000	823,000	1,619,000	39,373,000	1,791,000	394,000	7,803,000	11,107,000
1923	23,741,000	950,000	2,442,000	58,340,000	2,654,000	583,000	8,398,000	14,077,000
1924	13,707,000	548,000	3,392,000	79,639,000	3,624,000	796,000	7,294,000	15,106,000
1925	15,638,000	625,000	3,940,000	89,954,000	4,093,000	900,000	7,623,000	16,556,000
1926	14,186,000	587,000	4,565,000	101,642,000	4,625,000	1,016,000	7,505,000	17,711,000
1927	18,111,000	724,000	5,132,000	111,263,000	5,062,000	1,113,000	9,224,000	20,531,000
1928	21,579,000	863,000	5,856,000	124,242,000	5,653,000	1,242,000	9,752,000	22,503,000
1929	24,720,000	989,000	6,719,000	139,965,000	6,368,000	1,400,000	10,121,000	24,608,000
1930	27,296,000	1,092,000	7,708,000	157,966,000	7,187,000	1,580,000	10,262,000	26,737,000
1931	25,260,000	1,011,000	8,800,000	177,553,000	8,079,000	1,776,000	9,537,000	28,192,000
1932	23,477,000	939,000	9,811,000	194,033,000	8,829,000	1,940,000	8,495,000	29,075,000
1933	10,709,000	428,000	10,750,000	207,699,000	9,450,000	2,077,000	5,951,000	28,228,000
1934	41,968,000	1,679,000	11,178,000	207,658,000	9,446,000	2,077,000	8,300,000	31,003,000
1935	27,680,000	1,107,000	12,857,000	228,448,000	10,849,000	2,384,000	9,928,000	36,018,000
1936	14,262,000	571,000	13,964,000	253,271,000	11,524,000	2,533,000	8,759,000	36,780,000
1937	23,500,000	940,000	14,535,000	253,589,000	11,538,000	2,536,000	9,000,000	37,609,000
1938	24,440,000	978,000	15,475,000	262,554,000	11,946,000	2,626,000	9,360,000	39,407,000
1939	25,418,000	1,017,000	16,453,000	271,519,000	12,354,000	2,715,000	9,734,000	41,256,000
1940	26,435,000	1,057,000	17,470,000	280,484,000	12,762,000	2,805,000	10,123,000	43,160,000
1941	27,492,000	1,100,000	18,527,000	289,449,000	13,170,000	2,894,000	10,528,000	45,119,000
1942	28,592,000	1,144,000	19,627,000	298,414,000	13,578,000	2,984,000	10,948,000	47,138,000
1943	29,736,000	1,189,000	20,771,000	307,379,000	13,986,000	3,074,000	11,387,000	49,218,000
1944	30,925,000	1,237,000	21,960,000	316,344,000	14,394,000	3,163,000	11,842,000	51,359,000
1945	32,162,000	1,286,000	22,860,000	325,309,000	14,802,000	3,253,000	12,316,000	53,251,000

Estimated

Annual Costs computed for each year, starting with 1919.

Service life of highway elements taken as 25 years with no allowance for salvage value.

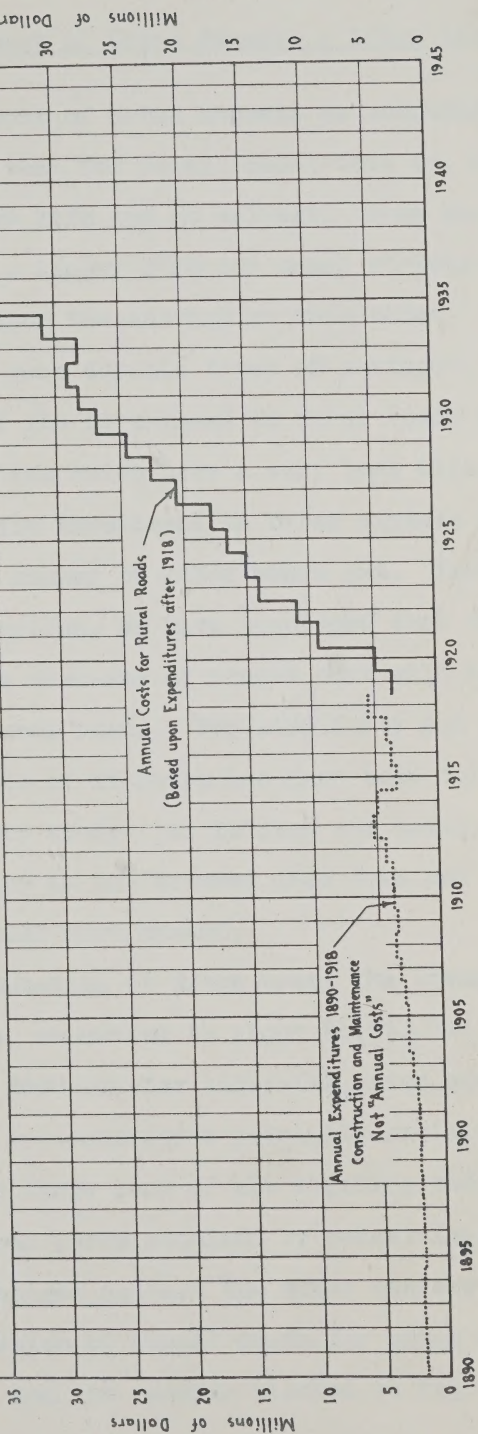
Beginning in 1937, Construction Costs are assumed as \$23,500,000 and Maintenance Costs as \$9,000,000 (averages for the preceding 10 years) and both are increased annually at the rate of 4% of the cost for the preceding year.

Interest on Unamortized Construction Costs taken at 4.55% (weighted average rate paid on Provincial indebtedness).

Taxes are taken at 1% of Unamortized Construction Costs.

ANNUAL COSTS FOR ALL RURAL ROADS IN THE PROVINCE OF ONTARIO-1918-36 PREDICTED ANNUAL COSTS-1937-45—RURAL ROAD EXPENDITURES-1890-1918

Annual Costs computed for each year starting with 1919.
 Construction Costs amortized over 25 years with no allowance for salvage value.
 Interest taken at 4.55% and taxes at 1.00 % of unamortized construction cost.
 In 1937 construction cost is assumed as \$23,500,000 and maintenance cost as \$9,000,000
 (average of costs for preceding 10 years). These costs are then increased annually at
 the rate of 4% of the cost for the preceding year, following registration trends.
 See Table I for Computation of Annual Costs.



RURAL ROADS

Computation of Annual Cost of Urban Streets - After 1918

The annual cost of urban streets is computed upon the same basis as that for rural roads; that is, assuming a 25-year average life and no salvage. Some authorities have allowed a longer life for urban streets than for rural roads, upon the assumption that urban streets are paved with more durable types of surfaces. On the other hand, much of the investment in rural roads is for grading and structures which have a very long life, whereas nearly all of the investment in urban streets is in the pavement, which sooner or later wears out. Taking all these into consideration, we have concluded that the average life of all the elements of street cost will be no longer than that for rural roads. For simplicity and uniformity, an average life of 25 years has been used for all classes of roads in this study. As pointed out later, a variation of a few years in the assumed life does not greatly change the annual cost amount.

In the computation of urban costs the items of lighting and sidewalks, amounting to about \$1,700,000 per year for lighting and \$500,000 for sidewalks, have been omitted. These costs are considered primarily social-necessity benefits. A large part of the lighting cost relates to sidewalks and parks required by pedestrians. These should not be charged against the motor vehicle users.

The computation of annual costs for urban streets is shown in Table II, and the results plotted in Fig. 6.

TABLE II
COMPUTATION OF ANNUAL COSTS FOR URBAN STREETS
PROVINCE OF ONTARIO - 1919-1945

Year	Construction Expenditures	Amortization Charges for Each Year's Construction (2) ÷ 25	Current Year's Amortization Charges	Unamortized Construction Cost at the Beginning of Each Year	Interest on Unamortized Construction Cost 4.55% of (5)	Taxes on Unamortized Construction Cost 1% of (5)	Maintenance Expenditures	Total Annual Cost of Urban Streets (4)+(6)+(7)+(8)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1919	\$3,297,000	\$ 132,000	\$ --	\$ --	\$ --	\$ --	\$3,037,000	\$ 3,037,000
1920	7,964,000	319,000	132,000	3,297,000	150,000	33,000	4,148,000	4,463,000
1921	12,236,000	489,000	451,000	11,129,000	506,000	111,000	3,743,000	4,811,000
1922	9,470,000	379,000	940,000	22,914,000	1,043,000	229,000	3,122,000	5,334,000
1923	14,258,000	570,000	1,319,000	31,444,000	1,431,000	314,000	3,649,000	6,713,000
1924	10,302,000	412,000	1,889,000	44,383,000	2,019,000	444,000	3,616,000	7,968,000
1925	7,457,000	298,000	2,301,000	52,796,000	2,402,000	528,000	3,487,000	8,718,000
1926	6,304,000	252,000	2,599,000	57,952,000	2,637,000	580,000	3,672,000	9,488,000
1927	7,651,000	306,000	2,851,000	61,697,000	2,807,000	617,000	3,574,000	9,849,000
1928	9,032,000	361,000	3,157,000	66,497,000	3,025,000	665,000	3,490,000	10,337,000
1929	13,085,000	523,000	3,518,000	72,372,000	3,293,000	724,000	4,227,000	11,762,000
1930	18,475,000	739,000	4,041,000	81,939,000	3,728,000	819,000	4,233,000	12,821,000
1931	21,630,000	865,000	4,780,000	96,373,000	4,385,000	964,000	4,658,000	14,787,000
1932	4,260,000	170,000	5,645,000	113,223,000	5,151,000	1,132,000	3,169,000	15,097,000
1933	4,372,000	175,000	5,815,000	111,838,000	5,088,000	1,118,000	2,711,000	14,732,000
1934	1,517,000	61,000	5,990,000	110,395,000	5,023,000	1,104,000	2,833,000	14,950,000
1935	3,575,000	143,000	6,051,000	105,922,000	4,819,000	1,059,000	2,755,000	14,684,000
1936	1,370,000	55,000	6,194,000	103,446,000	4,707,000	1,034,000	2,810,000	14,745,000
1937	8,500,000	340,000	6,249,000	98,622,000	4,487,000	986,000	3,450,000	15,172,000
1938	8,840,000	353,000	6,589,000	100,873,000	4,590,000	1,009,000	3,588,000	15,776,000
1939	9,194,000	367,000	6,942,000	103,124,000	4,692,000	1,031,000	3,731,000	16,396,000
1940	9,562,000	382,000	7,309,000	105,376,000	4,795,000	1,054,000	3,861,000	17,039,000
1941	9,944,000	397,000	7,691,000	107,629,000	4,897,000	1,078,000	4,036,000	17,700,000
1942	10,341,000	413,000	8,088,000	109,882,000	4,999,000	1,099,000	4,197,000	18,333,000
1943	10,754,000	430,000	8,501,000	112,135,000	5,102,000	1,121,000	4,365,000	19,089,000
1944	11,184,000	447,000	8,931,000	114,388,000	5,204,000	1,144,000	4,538,000	19,817,000
1945	11,631,000	465,000	9,378,000	116,641,000	5,307,000	1,166,000	4,719,000	20,570,000

Estimated

Annual Costs computed for each year, starting with 1919 (cost of sidewalks and lighting not included).

Service life of highway elements taken as 25 years with no allowance for salvage value.

Beginning in 1937, Construction Costs are assumed as \$8,500,000 and Maintenance Costs as \$3,450,000 (averages for the preceding 10 years) and both are increased annually at the rate of 4% of the cost for the preceding year.

Interest on Unamortized Construction Costs taken at 4.55% (weighted average rate paid on Provincial indebtedness).

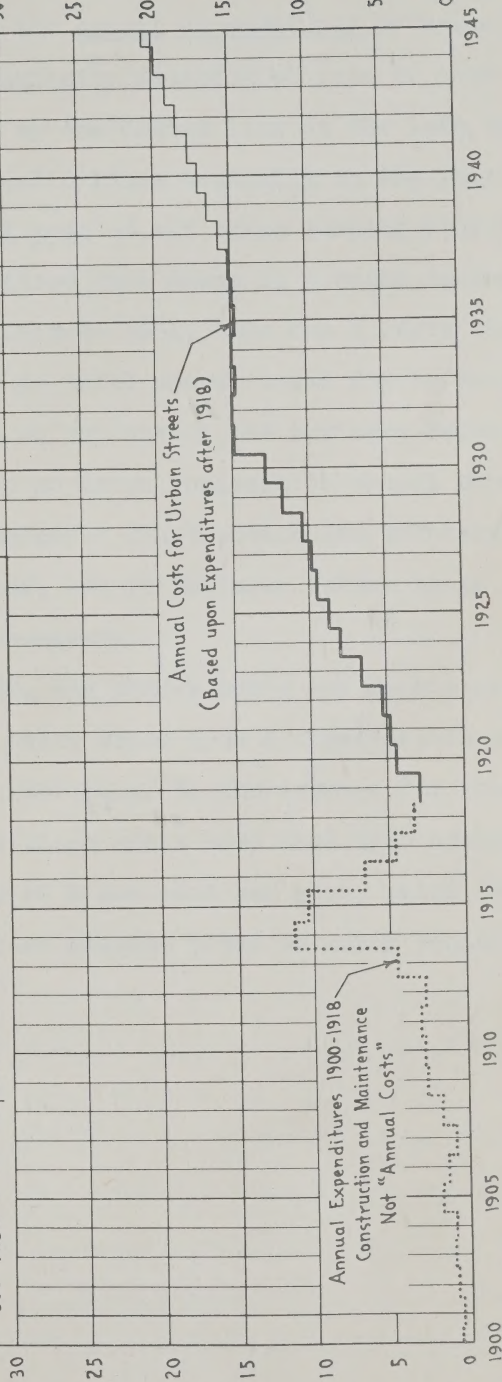
Taxes are taken at 1% of Unamortized Construction Costs.

ANNUAL COSTS FOR ALL URBAN STREETS IN THE PROVINCE OF ONTARIO - 1918-36 PREDICTED ANNUAL COSTS - 1937-45 - URBAN STREET EXPENDITURES - 1900-18

Annual Costs computed for each year starting with 1919, excluding sidewalks and lighting. Construction Costs amortized over 25 years with no allowance for salvage value. Interest taken at 4.55% and taxes at 1.00% of unamortized construction costs. In 1937 construction cost is assumed as \$ 8,500,000 and maintenance cost as \$ 3,450,000 (average of costs for preceding 10 years). These costs are then increased annually at the rate of 4% of the cost for the preceding year following registration trends.

See Table II for Computation of Annual Costs.

Millions of Dollars



URBAN STREETS

In Fig. 6 the annual expenditures by urban municipalities are graphically represented year by year from 1900 through to 1918 by the dotted line at the left of the diagram. The heavy solid line, beginning in the year 1919, represents the annual cost of all urban streets year by year. It will be noticed that there is a rapid increase in annual cost from 1918 to 1931, then for 4 years there was a flattening off in total annual costs due to retrenchment in expenditures on account of the business depression. As yet there has been no large increase in annual expense to make up for the deferred construction and maintenance in the previous period, but in the near future large expenditures will be necessary.

After 1936, the annual costs are herein represented as predicted costs based upon a construction and maintenance cost in 1937 equal to the average for the preceding 10 years, and these costs have then been assumed to increase at the rate of 4 per cent per year, which corresponds to the projected present trend of motor vehicle registrations.

Combined Annual Cost of Roads and Streets Compared with
Motor Vehicle Revenue - After 1918

Fig. 7 combines Figs. 5 and 6. It shows (at the left) a dash line representing the total annual expenditure on rural roads from 1890 to 1918. Superimposed above the dash line is a dotted line showing the total annual expenditure on urban streets (exclusive of sidewalks and lighting). The top line, therefore, represents the annual expenditures on rural roads plus the annual expenditures on urban streets.

Beginning with 1919, the full black line, which is at the upper limits of the cross-hatched band (diagonal shading), represents the annual cost of rural roads plus the annual cost of urban streets plotted above the base line, i.e., the lower horizontal line. The dot-dash line, which is the bottom of the cross-hatched band, represents the motor vehicle revenues which, it will be noticed, failed to reach the total annual costs by the amount represented by the cross-hatched band. It will be seen that the motor vehicle revenues paid only about half of the annual highway costs during the past 18 years.

From 1936 on toward the right, the motor vehicle revenues have been estimated on a basis of 4 per cent increase per year in registrations. The 1936 rates for registration prevail only through 1937, when a reduction in fees went into effect which causes the drop in the curve for 1938. The annual highway costs from 1936 into the

ANNUAL COSTS FOR ALL RURAL ROADS AND URBAN STREETS COMPARED WITH MOTOR VEHICLE REVENUES IN THE PROVINCE OF ONTARIO 1919 TO 1936 - PREDICTED ANNUAL COSTS AND MOTOR VEHICLE REVENUES 1937 TO 1945 - ROAD AND STREET EXPENDITURES 1890 TO 1918.

Figures on vertical lines are differences in millions of dollars between annual road and street costs and motor vehicle revenue for each year, 1919 to 1936.

Annual Costs for both Rural Roads and Urban Streets were computed on the basis of a service life of 25 years and no salvage value.

Annual costs and motor vehicle revenues after 1936 were estimated, on the assumption that motor vehicle registration, construction expenditures and maintenance expenditures will increase 4% annually.

See Tables I and II for computation of Annual Costs.

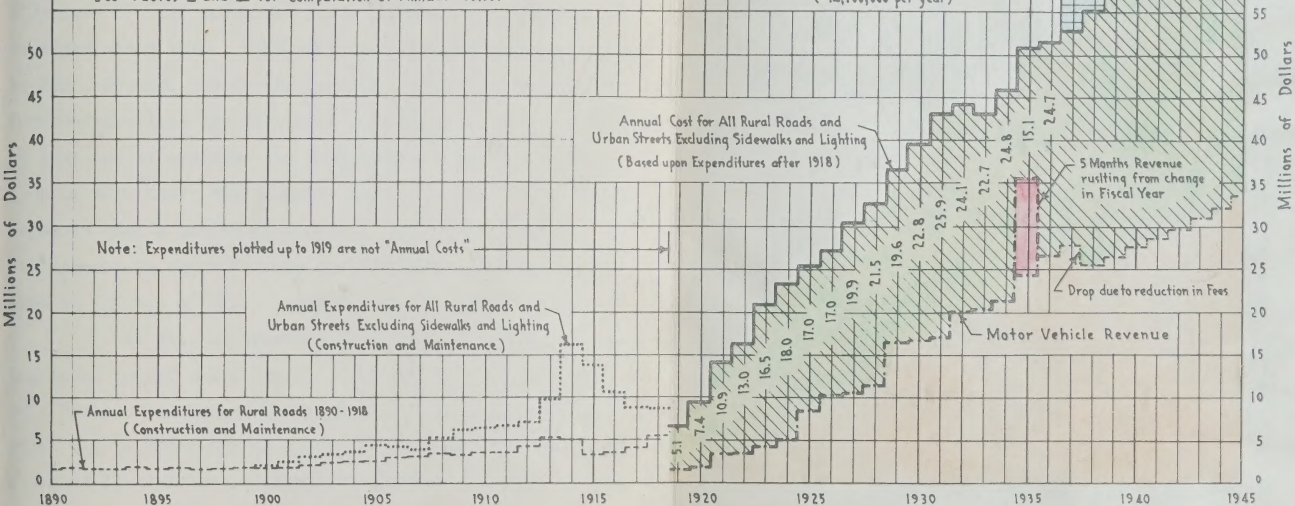


Fig. 7

future have been estimated as described above; these are represented by the line at the top of the cross-hatched band.

The space between these upper two curves (the cross-hatched band) represents the amounts the revenues received from motor vehicles have fallen short of reaching the annual costs. This shortage represents the subsidy year by year which the motor vehicles as a class have received since 1918. From 1918 to 1937 this subsidy amounts to \$326,000,000, and if the present rates of motor vehicle fees and gasoline tax continue, this subsidy will continue to increase as shown by the cross-hatched band. If, beginning with 1937, this subsidy should be paid off in equal payments over a period of 50 years, the annual payments will amount to about \$14,100,000 per year, as shown by the area at the top of Fig. 7 shaded with horizontal lines.

It will be remembered that the line representing total annual costs in Fig. 7 is extended beyond 1936 on a basis of an annual increase of 4% over the preceding year. It is difficult to estimate how much money will be expended for road improvements in the next 10 years. The Province is entering into a period which demands 4-lane roads on heavy traffic arteries; this type of construction is expensive. The elimination of grade crossings for both railways and highways are also expensive projects; much of this work is still ahead. The larger the highway expansion program is, the greater will be the annual costs and the accumulating deficit.

Subsidy, or Highway Debt, also Charged to the General Public

It has been shown that the accumulated subsidy as of January 1, 1937, represented by the difference between the total annual cost since 1918 and the revenues obtained since 1918 from motor vehicles, amounts to \$326,000,000. Since this amount has purchased highway elements that have a limited life, this debt should be amortized over some period of years. We have arbitrarily set up this amortization over a period of 50 years beginning with 1937 and have allocated payments and interest on this subsidy as an equal annual charge of about \$14,100,000 over that period. During the next half century either motor vehicle users or the general public, or both, must pay their share of this charge in addition to the annual highway costs. The motor vehicle users have already had the benefits of this subsidy, and in a measure will continue to have the benefit from it because the road elements which it provided are still in service. That this is not a book-keeping debt is well supported by the fact that of the Provincial debt, \$224,639,000 had been invested in rural highway construction during the period under review, as given in the Dominion Bureau of Statistics. This does not include the money borrowed by cities for street improvements.

In this analysis it will be recalled that none of the cost of roads and streets that existed prior to 1919 was charged against the motor vehicle. That was considered to be a fair payment by the public for so-called social-necessity use, and after 1918 the motor vehicle was to be charged the total annual cost of highways and streets. But in the 18 years that have elapsed, a large highway deficit has rolled up, so large that it seems to be too great a burden to place upon the motor vehicle user. It has therefore been arbitrarily allocated to the general public merely as a matter of expediency. There is no other excuse for this disposition of the debt. The public will have to pay about \$14,100,000 annually for the next two generations to remove the highway deficit that has accumulated in 18 years. It is assigned to the public only with the understanding that beginning with 1937 the total highway and street costs will hereafter be charged to the motor vehicle users.

Discussion of the Effect of Service Life and Salvage Value upon Annual Costs

The standards of highway design and construction developed during the last twenty years have not been in use long enough to develop accurate statistics as to their probable life and salvage value. Consequently, the life and salvage value must be estimated, based upon the observations and opinions of those familiar with highway work. Hence, there may be a wide range of opinion as to what values should be used. Obviously all elements of the highway structure do not have the same life. The pavements are usually the least durable elements. Grading and structures will last a long time, providing the location is favorable and the factor of obsolescence does not enter. Likewise, some elements of the highway will have a considerable salvage value remaining at the end of their useful life and other elements will have none. If the highway is unfavorably located from a traffic standpoint, is unsafe or inadequate, the entire highway structure may have to be abandoned and its salvage value will then become zero. Considerable uncertainty exists today as to the requirements for future highway improvements.

In this report, annual costs are computed beginning with 1919. Generally speaking, the work done since 1918 has been in the nature of acquiring new locations, widening pavements, widening fills and cuts, flattening curves, reconstructing bridges and principally the

reconstructing of pavements. Some of these highway elements will have a considerable life, namely, the right-of-way, fills and cuts, and bridges; these improvements may last 40 or 50 years or even longer. Other capital expenditures in that period, especially those for pavements, will have a shorter life - some of them 10 years, others 15, 20 or 25 years. A strict analysis would require determining the life of each element of the highway which these capital expenditures produced and amortizing that expenditure over its useful life.

In connection with this report, an attempt was made to assign reasonable life and salvage values to all of the elements of highway cost which entered into the capital expenditures in the period under review. This was done by separating the construction on all rural roads into four general classes: King's highways, county roads, township roads, and roads lying in the Northern Development. In each of these classifications, the different elements of road construction such as grading, structures and pavements, were assigned probable life and salvage value based upon our previous experience and upon the answers of the Ontario Highway Department to questions pertaining to the life of highway elements. The different types of pavements, concrete, bituminous, gravel, etc. were each given a reasonable life and salvage value according to their separate characteristics.

As a result of these studies, we have concluded that the average age of all road elements purchased during the period under review (1918-36) is about 25 years. There will probably be a salvage value remaining at the end of this 25-year period, but we have assumed that value to be zero on the theory that applied science is so rapidly producing modifications in transportation facilities that it is probably unwise for the present generation to assume that its expenditures have much salvage value which will be beneficial to the next generation.

Other students of this problem have come to the conclusion that it is advisable to assume no salvage value at the end of the average life of the highway elements, and have reached the conclusion that the average life of all highway elements is from 25 to 30 years. The following quotation is typical - from "The Economics of Highway Planning" by Oregon State Highway Commission, September 1937, page 214:

"Perhaps a word in conclusion is in order regarding the adoption of 30 years as a maximum amortization period for all improvements. This value represents about the life of one generation. It is about the maximum time period for which it is at all possible to predict trends and tendencies in traffic and industrial development. Even within this period future predictions may be in error, but beyond this, they can be regarded as no more than conjecture. The permanency of highway improvements is based upon their ability to function for the purpose for which they were created. Their ability is in turn a function of traffic and industrial needs. Within the 30-year period above assumed, these needs can be predicted with at least reasonable assurance of

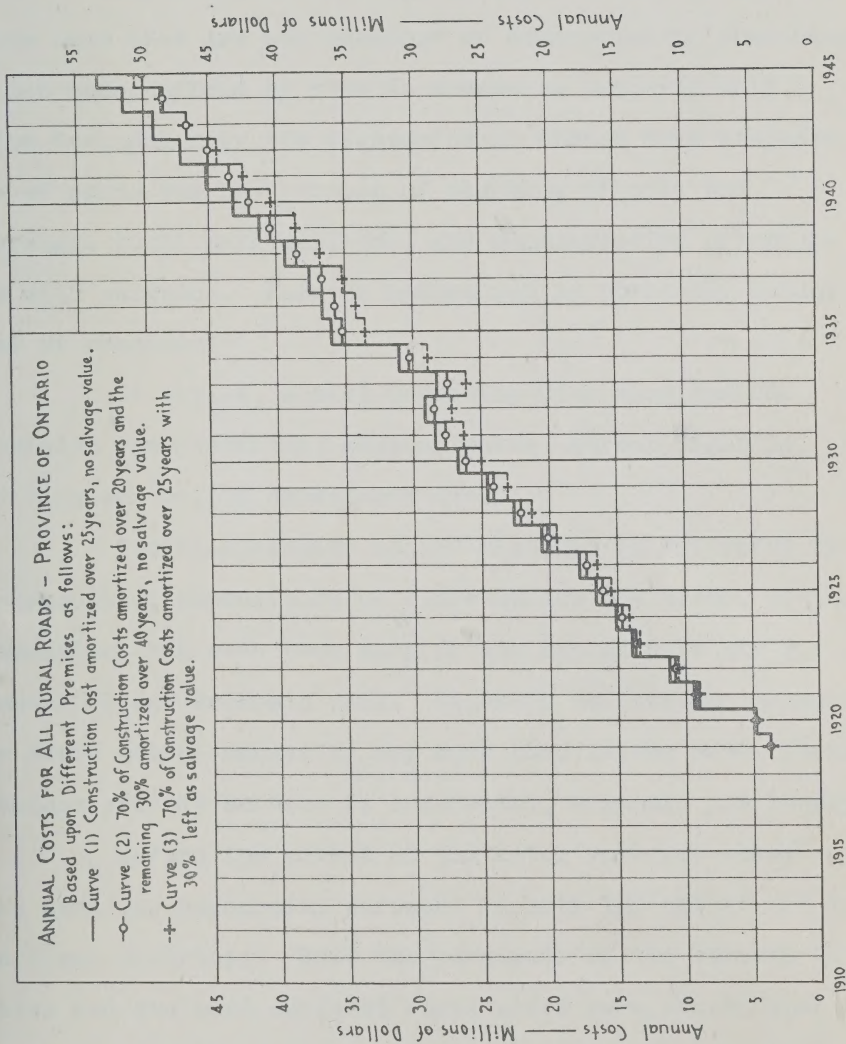
accuracy. Beyond this value, the best of estimates is of extremely doubtful value. It would appear, therefore, that any sound basis for economic analysis should comprehend the amortization of all investments within a period not greater than this, regardless of the permanency which the improvement in question seems to possess at the time of its initiation."

As a matter of fact it makes little difference what assumptions are made regarding the life of highway elements and their salvage value, provided they are within reason.

In order to illustrate this point, Fig. 8 has been prepared in which annual costs are shown based upon different assumptions as to the life and salvage value of the different highway elements. The assumptions made in Fig. 8 embody a fairly wide range of plausible opinions, yet the resulting curves of annual cost all fall fairly close together; from which we must conclude that the assumptions made in this report, to the effect that all construction costs may be amortized over a period of 25 years with no salvage value, has substantially the same effect upon the annual costs as any of the other assumptions which require more complicated calculations.

The reason why these curves fall close together is because, if the life of a highway element is lengthened, the yearly amortization charge is reduced but the interest cost on the unamortized capital is increased, and these effects tend to balance each other. If the allowance for salvage value is reduced, the yearly amortization charge is increased but the annual interest on the unamortized portion becomes smaller, and these effects tend to balance each other.

Fig. 8



Total Annual Road Costs - Portion Charged for Social-
Necessity Uses.

Social-necessity uses in rural districts include those uses that are not economic or commercial in character. It has been defined by some as access to property only which includes only the right-of-way; others have included use of roads for the purpose of reaching schools and churches, rural mail delivery, and communication of neighbor with neighbor. Farm to market use is obviously commercial or economic.

In cities, social-necessity uses also include provision for sidewalks, sewers, water, street lighting, and fire and police department uses.

Social-necessity use of highways is reflected by the amount of expenditure on roads before the advent of the automobile, but even then much of the expenditure was for commercial and economic uses. Highways and streets do not now serve social-necessity any more than in the past. Their greatest present service is commercial, economic and luxury.

Before the advent of the motor vehicle, roads were used for commercial purposes in both the cities and in the rural districts. Both the pavements of the streets in cities and the hard surfaced rural roads were constructed largely to facilitate commercial travel, for the transportation of industrial raw and finished products in the cities and for the transportation to market of farm products in the rural districts. It is true that these users of the

roads were not taxed as such, but it is indisputable that the pavements in city streets and the graveling of county roads were not impelled by the urge of social-necessity as much as for commercial requirements.

In a strict analysis, we should therefore separate, as equitably as we can, those road costs (before the motor vehicle appearance) that were for commercial requirements from those which were for social-necessity requirements for both the rural and urban districts. This is not a simple problem and its answer is therefore not too obvious.

One of the most common methods of approach to this problem is to determine, from a study of the annual costs prior to the advent of the motor vehicle, the amount the general public was willing to pay for roads and to adopt a lesser amount (because some of the early expenditures were for commercial and economic purposes) as the annual highway cost which should be borne by general taxation and to project this annual cost through the period affected by the motor vehicle. A modification of this idea assumes that the amount raised through general taxation should be a per capita amount which is evidenced by the per capita expenditure prior to the motor vehicle era, and that this per capita amount should be extended through the period affected by the motor vehicle.

A further modification involves expressing the average per capita expenditure for highways before the motor vehicle came as a percentage of the total present per capita

expenditure, and then assume that this percentage of the total annual cost represents the charge to the public for social-necessity throughout the period under review.

Another approach is exemplified by the disposition made by the Salter Conference of Great Britain. The Salter report disposed of the social-necessity use by adopting a certain year when all highway debt was accepted as an obligation to be paid through general taxation, and from that date on, charged to the motor vehicle users the total annual cost of roads.

Before the advent of the motor vehicle, the radius of use of commercial vehicles was, generally speaking, the distance a horse could travel with a load and return the same day, and no charge against commercial vehicles as such was made except on toll roads where the traffic was largely commercial and the distance traveled was relatively long. With the advent of the motor vehicle, the commercial range of highway use greatly increased and the numbers of vehicles tremendously increased. These two factors have made the highways take on a much different commercial significance, and it has become no longer equitable to meet highway costs from general taxation.

Because it is simple and because it permanently disposes of a controversial matter, we have adopted the Salter idea.

First we have charged to the general public all the total cost for roads and streets prior to the year 1919, even though these roads and streets were available for motor

vehicle use during the period 1919-36. Secondly, we have assigned to the general public the amortization of the large highway debt accumulated during the period 1919-36. From the present time on the motor vehicle user is charged the total annual cost of roads and streets (excluding sidewalks and lighting) and no deduction is made from these costs for so-called social-necessity use.

The Salter Conference charged all costs to the motor vehicle users in 1930 which was the year in which they deliberated; there was no special justification for specifying that year. We have assumed that the motor vehicle users were just responsible for all costs after 1918, because in 1919 expenditures rose sharply and continued to rise as shown in Figs. 2, 3 and 4. This abrupt rise could in no way be attributed to social-necessity demands; it was definitely and completely the result of motor vehicle use. From 1919 on motor vehicle registrations increased rapidly and expenditures mounted.

During the period 1919-36 motor vehicle revenue failed in every year to meet annual highway costs, and a deficiency, or debt, of \$326,000,000 accumulated. This debt we have arbitrarily left for the public to pay, thus placing upon the general public a burden which far exceeds any reasonable allowance for social-necessity use.

Allocation of Annual Road Costs--Discussion of Methods
of Allocation to Different Types of Motor Vehicles.

The allocation of annual costs among different types of vehicles should be based upon the cost of the facilities which they require and the use which they make of these facilities. Several methods of allocation have been propounded which, in varying degrees, take these fundamental requirements into consideration. Six possible methods of allocation are described below, and the extent to which they satisfy these fundamental requirements is pointed out.

I. Allocating annual highway costs on the basis of vehicle miles. This method assumes that all vehicles produce a like annual road cost. It amounts to the conclusion that if a Ford car travels a mile over a highway it costs the same as it would cost to carry the heaviest truck over the highway. It assumes that a highway adequate for a Ford car costs as much as a highway adequate for the heaviest permissible loaded truck and trailer. This method does not take into account the cost of facilities required, and only partially accounts for use made since all vehicles are treated as though they were of the same weight.

II. Allocating annual highway costs on the basis of occupancy of the highway. This method takes into consideration the volume of the vehicle, its speed, and its annual mileage. Since heavy trucks occupy very much greater space and travel slower than passenger cars and operate much

greater mileages, this theory of allocation would result in a charge to the heaviest permissible unit of 200 to 300 times the charge to the passenger car (See Fig.18). Road occupancy is a measure of road use. It does not take into consideration, however, the cost of facilities required, because it omits the vehicle weight factor which greatly influences highway costs.

III. Speed ton-mile allocation. The Salter Commission in Great Britain studied a method which would take into account the distance traveled by a vehicle, the weight of the vehicle and the average speed of the vehicle, and developed a factor called a "speed ton-mile" which could be used to allocate costs to different types of vehicles. The State of Washington also attempted to develop a similar factor. In both studies, this method of allocation was abandoned as being impracticable, largely because of the difficulty in determining reasonable average speeds for the different types of vehicles. This method, if practical would take into account road use to a fuller extent than the other methods proposed, but it does not take into account the cost of facilities required.

IV. The Increment Method. This method involves allocating to different types of motor vehicles an equal proportion of those annual costs required for highways adequate for the basic vehicle, namely, the passenger car and its equivalent light truck, and to heavier vehicles a progressively additional amount representing the cost of their special requirement. This method is based upon the prin-

iple proposed by the Joint Committee of Railroads and Highway Users of the U.S.A., which was composed of the officials of the larger railways and the officials of the larger motor vehicle interests. They held a joint conference in 1932-1933, and after deliberating on many controversial matters, disagreed on several points and agreed on others. They agreed on the following principle of taxation:-

"63. The apportionment of special taxes among motor vehicles of various types should be based upon use of facilities required and should be sufficient to pay their fair share of total annual costs. Separate schedules should be determined for passenger automobiles, buses, and trucks.

"64. The basic cost of constructing, improving and maintaining a given highway should be determined from a highway designed for private passenger vehicles and other vehicles commensurate therewith. All vehicles using such highways should pay their proportionate share of that total as a base tax. The total additional cost of construction, improvements and maintenance to make a road suitable for a type of vehicle requiring such additional cost should be shared by each vehicle of that type and each vehicle of greater size. Thus, each group should share in the base cost plus all increments of cost up to and including cost required by it."

Many have assumed this to be the most equitable basis for allocation of motor vehicle taxation because it was agreed upon by a most representative body of the two great competing transportation agencies in the United States.

In approaching this subject, the most logical method is first to determine the annual costs which are required to provide highways wholly adequate for the basic vehicle and then to determine the additional cost made necessary to provide adequate highways for the heavier vehicles step by step as these heavier vehicles increase in wheel load and in total load. Consideration must also be given to other added expenses incurred for the heavier and wider vehicles, such as for additional width of pavements, the additional strength of bridges, flattening of grades, additional lanes, and any other elements of cost which pertained to the problem.

The general conclusion reached in this report is that the thickness of pavement required varies with the square root of the wheel load. While it may not seem obvious that the total annual cost of a pavement varies directly as the square root of the wheel load, nevertheless, when one gives due weight to the other additional costs such as width, additional lanes, delays to other vehicles, hazards, damage to existing pavements, greater occupancy of the road, etc., the conclusion is reached that the annual cost also varies at least as the square root of the wheel load. This method is more often hereafter referred to as the "square root of the wheel load method"; it is the "increment method".

The "increment", or "square root" method, relates to the facilities required; it does not adequately allow

for the use made of facilities.

V. Straight Ton-mile Method. The ton-mile has been long accepted as a measure of commercial transportation as it takes into account both distance traveled and loaded weight of vehicle. The straight ton-mile basis results in a fixed rate of charge per ton-mile which when applied to the total ton-miles of traffic will yield the total annual highway cost. The highway cost will, of course, depend upon the facilities which are provided. Consequently, if a few extra heavy vehicles demand expensive highway facilities, the lighter vehicles which do not require such facilities will be compelled by the straight ton-mile method to subsidize the heavy vehicles in order to produce the total highway cost. The straight ton-mile method has the effect of greatly overcharging the lighter vehicles and undercharging the heavier ones because there are too few of the latter to produce their fair share of cost. In other words, the method takes into account use made but does not equitably charge for facilities required; it makes the light vehicle pay for facilities it does not require.

VI. Combined Increment and Ton-Mile Method. Of the methods described above, the increment and the ton-mile methods have both been accepted and used by authorities on allocation. Neither of these methods, however, fully takes into account both the cost of facilities required and the use made of them. We have, therefore, developed and applied the following two methods which combine the incre-

ment and ton-mile methods in such a way as to allocate costs in accordance with both facilities required and use made.

One application of the combination of the square root-and-ton-mile method involves allocating costs between classes of vehicles on the square root basis and then within each class allocating costs between the vehicles of that class on a straight ton-mile basis.

The other application involves charging to the basic class as a whole the amount determined by the square root (increment) method and then distributing among the different types of basic vehicles in direct proportion to ton-miles, as was done in the above method. The remaining cost to be shared exclusively by all vehicles heavier than those in the basic class is allocated among these heavier classes on a ton-mile basis, but at an increasing ton-mile rate per class. By this method not only are the vehicles charged in proportion to the cost of highway facilities which they require, but the charges relate to the extent of their use of such facilities expressed in ton-miles.

The report will first deal with Method IV, the square root of wheel load (increment) basis; it will then discuss Method V, the ton-mile basis, and then the adopted Method VI which is a combination of IV and V.

SQUARE ROOT OF THE WHEEL LOAD BASIS FOR ALLOCATION

General Relation between Wheel Load and Thickness of Pavement

Any load on a pavement is distributed through the pavement in some such manner as represented by Figs. 9 and 10. This is a well-known fact and the theory has been proved to be sound because when pressure recording devices are applied to the underside of pavements or in the subgrade below the pavement and the pressure distribution is measured, it is found that the pressure directly under the wheel is the greatest and that it gradually grows less outward from that point. While this pressure distribution extends outward for some distance it is so small toward its outer fringe as to be negligible. Therefore, it is reasonable to draw two diagonal straight lines from the top of the pavement toward the bottom, as in Fig. 10, and to assume that all weight is distributed on the subgrade at the bottom of the pavement over a circular area defined by the base of a cone, the limits of which are represented by these two diagonal heavy lines marked "Assumed Limits of Load Distribution". Consequently, if the pavement is thicker, these lines diverge farther and hence describe a bigger area over the subgrade. Different subgrades will support different intensities of loads. Hence, if we can determine the intensity of pressure that a given subgrade can support, it

is only necessary to make the pavement thick enough so that the area over which the load is distributed divided by the wheel load will not exceed the permissible supporting pressure on the existing sub-grade. It follows that for a given subgrade the heavier loads must be distributed over greater areas and will require thicker pavements than the lighter loads because the size of the circle of distribution can only be increased by thickening the pavement as shown in Fig. 9. Later it will be shown that the required increase in pavement thickness is proportional to the square root of the wheel load.

The stiffer pavements (such as concrete slabs) distribute their loads over larger areas than the more flexible pavements, such as bituminous pavements or gravel pavements. This is the reason why, on the thoroughfares over which the heavier trucks and buses operate, concrete pavements have proven to be more economical in general than to provide thick bituminous pavements. In fact, concrete pavements were the direct product of heavy truck requirements.

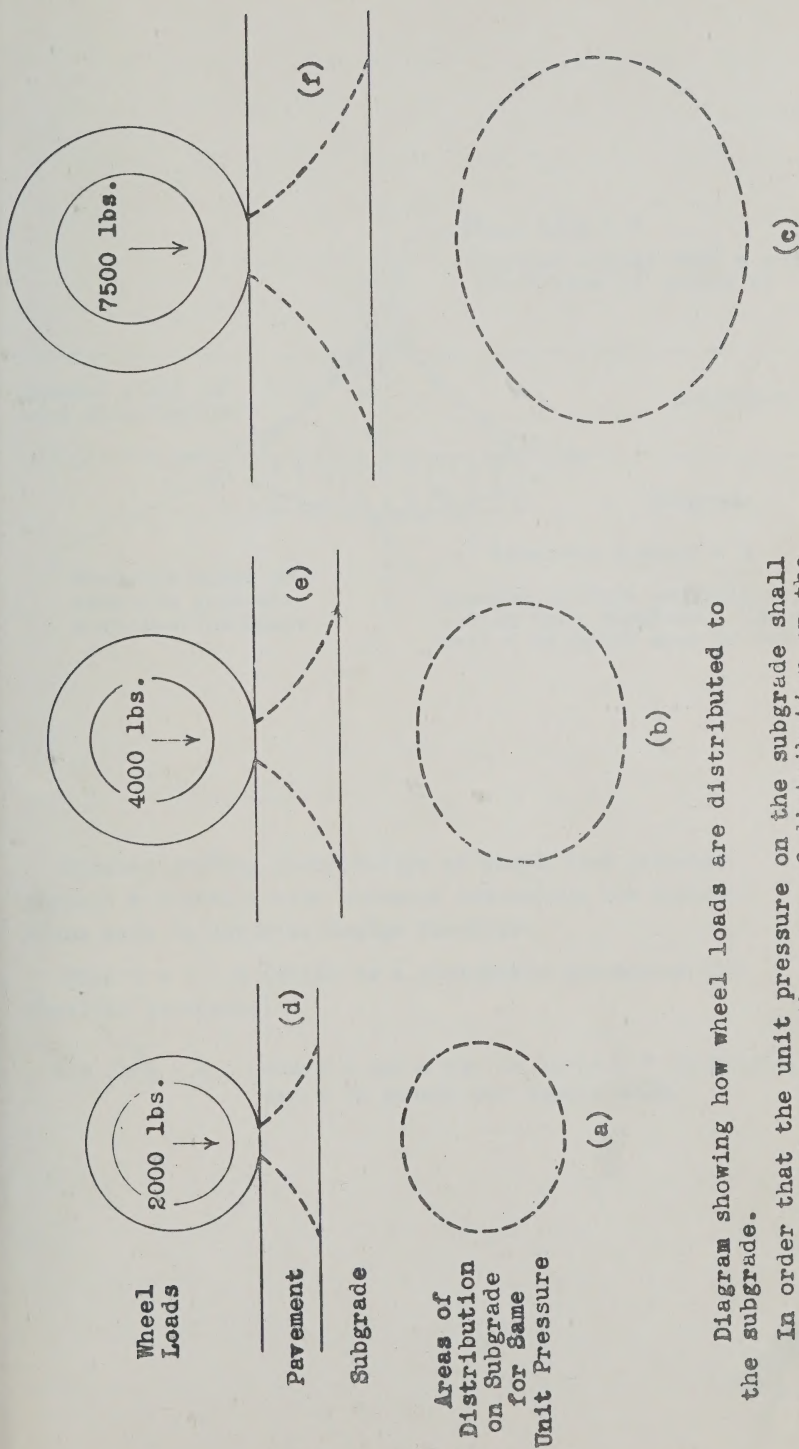


Diagram showing how wheel loads are distributed to the subgrade.

In order that the unit pressure on the subgrade shall be the same in all cases, the area of distribution on the subgrade must be increased with the wheel load as shown in (a), (b) and (c). This is accomplished by thickening the pavement as shown in (d), (e) and (f).

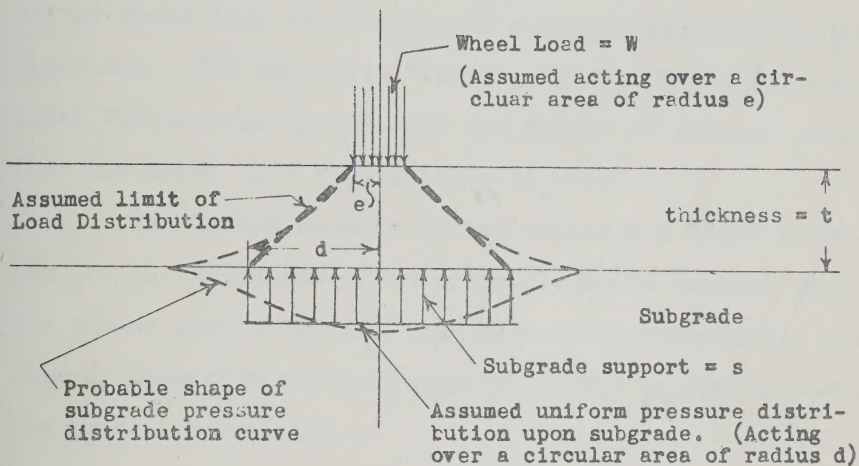


Diagram showing distribution of wheel load pressure through a flexible type pavement indicating the assumptions made in deriving design formulas.

When $d = t + e$ (which is a reasonable assumption for flexible pavements)

$$t = \sqrt{\frac{W}{\pi s}} - e \quad \text{where } t \text{ and } e \text{ are in inches, } W \text{ in pounds, and } s \text{ in pounds per square inch.}$$

Fig. 10

Square Root Relation - Cement Concrete Pavements

Every approach to the theory of design of concrete pavements has developed a formula in which the square root of the wheel load has a definite multiple relation to the thickness. The so-called "Corner" theory, the more complicated Westergaard theory, and the result of general practice has shown this relationship to hold.

The Corner Formula (often called the Older formula) for the thickness of concrete pavements assumes that the corner portion of the slab acts as an unsupported cantilever beam with the load applied at the extreme corner. The general formula is

$$t = \sqrt{\frac{KW}{f}}$$

where t is the thickness of the slab in inches

W is the wheel load in pounds

f is the allowable working tensile stress
in bending for the concrete

K is a number (coefficient) which depends
upon the type of joints and reinforcing
used in the pavement.

The formula as originally developed for an isolated corner has the form $t = \sqrt{\frac{3W}{f}}$. Where two corners are joined together by reinforcing or by a tongue and groove joint, as is usually the case in the interior of the pavement, the form $t = \sqrt{\frac{1.5W}{f}}$ is often used, giving a thinner pavement in the center than at the edges. This is the design basis for all thickened edge types of cross-section such as the adopted standard in Ontario. Other coeffi-

cients have been suggested for use in the corner formula in order to take into account impact or varying sub-grade support, but whatever value is used for K in the general formula, the relation still holds that, for a given set of conditions, the thickness required varies directly with square root of the wheel load.

The theoretical Westergaard formula (Public Roads - April 1926) is complex in form, but it also involves the square root of the wheel load relation in combination with other terms.

The statement has been made that in the design of pavements, subsoil and climatic conditions (changes in temperature) control the pavement thickness, which is not true. It is equivalent to saying that wheel loads do not control thickness of pavements.

Subgrades should be drained so that the water which tends to soften the subgrades will be carried away in ditches to natural water courses. This is an economic precaution which any competent highway engineer would take in constructing any road whether it be of earth, gravel, bituminous material or concrete. After this has been accomplished, there still remains the problem of designing the road to support the vehicle loads. Modern practice indicates that weak subgrades can be made to produce greater bearing value at moderate expense, and this so-called "stabilization of subgrade" is being practiced by many Highway Departments.

One of the common contributory causes for the failures in pavements in northern climates, such as Ontario, is the heaving of the pavement due to frost and the softening of the subsoil in spots here and there when thawing; a condition that is sometimes known as "frost boils". Proper drainage of the subsoil and removal of improper subsoil and replacing it with granular material, such as sand and gravel, will prevent frost heaving and soft spots from occurring in the spring. Thickening of the pavement will not cure these defects. After the subgrade has been corrected (regardless of whether it is corrected by drainage or some other method), then the thickness of the pavement depends upon the wheel loads it must carry.

It is perfectly obvious that a 2000 lb. wheel load will require, through the application of well-known theories of design, a pavement of a given thickness and that on the same subgrade by the application of the same theory a wheel load of 7500 lbs. will require approximately twice (1.93) the pavement thickness, otherwise the pavement will break due to the heavy wheel loads. The latter pavement is obviously over-designed for the lighter wheel loads.

To say that the pavement has to be as thick for passenger wheel loads as is required for the wheel loads of heavy trucks is absurd. It is the same as saying that when the heavy truck travels over a pavement it does no more damage than the ordinary passenger car. This is only nearly true when the pavement is properly designed for the

heavy truck, but it is not true at all when the pavement is designed only for passenger cars.

The standard design for the ordinary concrete sidewalk is 4" thick. Passenger car owners drive their cars daily over these 4" sidewalks in going to and from their private garage on their residential property without the slightest damage being done to the sidewalk. It obviously does not require, therefore, the advice of a highway engineer to convince any one that a typical 4" sidewalk is adequate for passenger vehicle wheel loads. Now, suppose heavy trucks crossed over a sidewalk as many times as passenger vehicles do, the sidewalk would be ruined in a matter of a few days if not by the passage of the first truck. Climatic conditions were the same in both cases, but the sidewalk could carry the light passenger car loads and could not carry the heavy truck.

To cite one specific instance, at the time the World's Fair was in operation in Chicago it became advisable to divert passenger vehicle traffic, including a large number of taxicabs, over a considerable stretch of the ordinary 4" sidewalk which had been in existence for many years. This passenger vehicle traffic, composed of about one million taxicabs and official cars, passed along this sidewalk during the season of 1933, without any appreciable damage to the sidewalk.

This is only one instance of thousands of examples that could be cited as practical experiments which show conclusively that concrete pavements adequate for passenger vehicles need only be about 4" in thickness, provided the subgrade is properly prepared. This agrees perfectly with the theories of design which have been accepted as sound practice in the design of concrete pavements.

Concrete pavements contract and expand with changes in temperature; they also warp and change their shape with changes of temperature and moisture. Consequently, it is impossible to absolutely predict what kind of a support the pavement may have under different seasonal conditions. Concrete is strong in compression but is weak in tension; i.e., it will stand a large force tending to crush it, but will only withstand a small force tending to pull it apart.

When a concrete slab, like a pavement, contracts because the temperature is lowered, it has to drag the pavement over the subgrade on which it rests. There is a very considerable amount of friction between the subgrade and the concrete slab; consequently it is unable to drag only a limited length of slab before it will crack.

There is another phenomenon which occurs in concrete pavements which should be clearly understood. When they are heated on the top surface due to the sun's rays, this heat is not rapidly transferred to the bottom of the pavement; consequently the bottom is cooler than the top.

Hence the top expands more than the bottom and the pavement tends to arch up in the middle and be unsupported by the subgrade along its middle line. On the other hand, at night the pavement becomes cooler on the top than it is on the bottom and consequently curl up at the edges; it becomes unsupported on the edges although it is fully supported along its middle line. It is obvious, therefore, that the most vulnerable parts of the concrete pavement are the unsupported edges and corners, especially at the transverse joints. Observations have shown, beyond any doubt, that the outer edges and the outer corners of pavements curl up due to temperature changes, so that they may not be lying on the subgrade at all. This phenomenon is the basis for the corner formula for design described above.

In recent studies of this phenomenon made by the U. S. Bureau of Public Roads*, the conclusion was reached that the thicker the pavement the more likelihood there was of developing stresses due to changes of temperature that were critical, and that the only way to avoid cracks in concrete pavements was to make planes of weakness at 10-foot spacing, and that if the pavement was finally broken up into 10-foot squares the curling of the small slabs would not be sufficient to develop serious tensile

* "PUBLIC ROADS" November 1935

stresses, and that then such small slabs would have to be designed for wheel loads only. There are many road slabs 60 ft. or more in length that have been in service for many years and have not cracked into 10-foot lengths. This does not mean that they will not ultimately do so; it means that the conditions for fracture have not occurred in them, i.e., the critical combination of wheel load and internal stresses have not occurred sufficiently often to crack them.

It is a well known fact that concrete will withstand a given tensile stress developed, say by wheel loads, and not break but if this wheel load is repeated a sufficient number of times the slab will break. This is why pavements withstand certain types of traffic for a while and then suddenly go to pieces. It has been found that if the tensile stress, set up by wheel loads in the concrete slab, is greater than one-half the breaking tensile stress of the concrete (called modulus of rupture) that this concrete slab will ultimately break due to fatigue.

It is certainly true, therefore, that climatic conditions must be taken into consideration in designing concrete pavements. This is done by properly draining and stabilizing the subgrade, as explained above, and by the introduction of sufficient number of planes of weaknesses where the concrete slab can crack transversely if the stress becomes sufficient. These conditions of design are present whether or not there is a light or a heavy wheel load, and they must all be taken into consideration first, after which

the design of the pavement thickness is directly proportional to the square root of the wheel load.

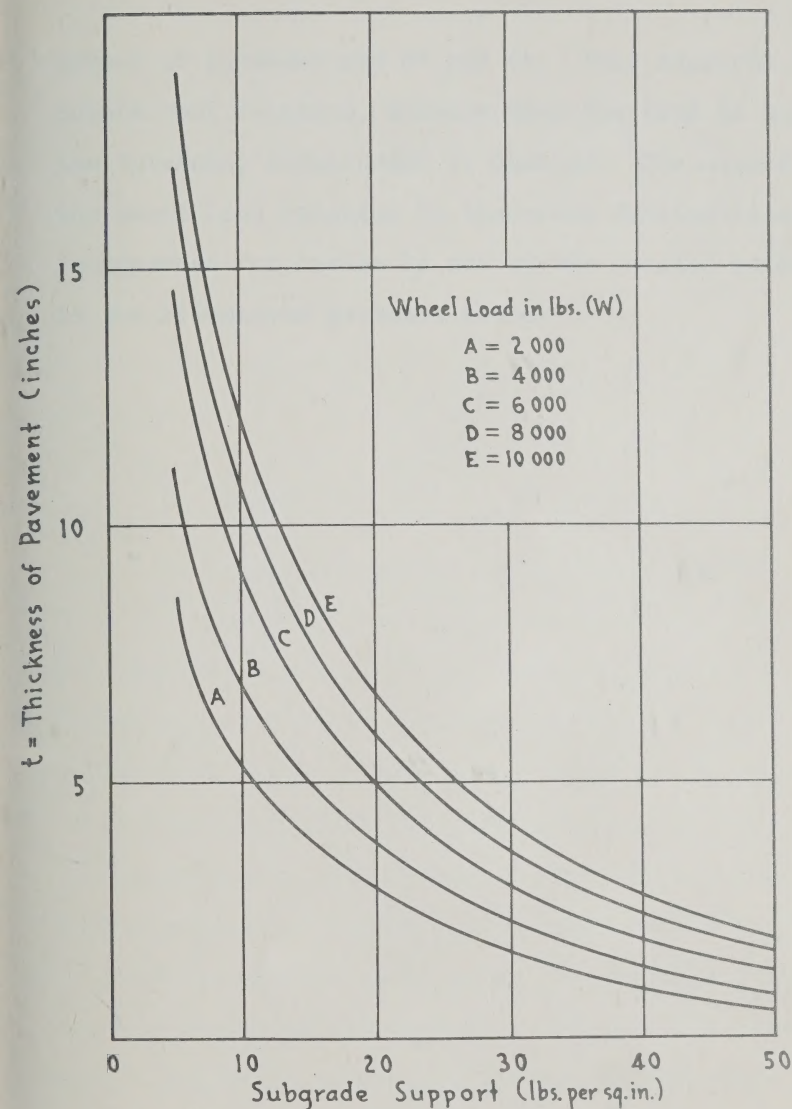
Until 1930 it was customary in Ontario to design the thickness of the edges as 6" with no layer of gravel under the pavement. The present design requires an edge thickness of 10" and also 6" of gravel under the pavement, which would be equivalent in cost to making the pavement 12" thick at the edges without any gravel layer. Stating it in other words, practice in Ontario has shown that pavements should be approximately twice as thick at the vulnerable edges for trucks and buses as the concrete pavement adequate for the basic vehicle. In fact, when these pavements were constructed 6" thick on the edges, they were not suitable for the use of motor vehicles which were much heavier than the basic vehicle. We may assume that the wheel load of the heaviest basic vehicle is 1800 to 2000 lbs. It includes the heaviest passenger car and the light deliver or farm trucks. The heaviest wheel load allowed in Ontario is 7500 lbs. The ratio of these wheel loads is 1 to 3.75, and, on the square root basis, the thickness of a pavement adequate for the heaviest truck would be about twice the thickness required for the basic vehicle.

Theory and practice, therefore, go hand in hand in the obvious conclusion that the heavier the wheel load thicker the pavement must be, irrespective of the climate or the subsoil conditions.

Square Root Relation - Bituminous Pavements

In the construction of bituminous pavements, it is even more necessary to drain the subsoil, to remove unsuitable subsoil material and substitute granular material, than it is for rigid types of pavement. This having been done, the thickness of bituminous pavements varies as the square root of the wheel load. It appears in textbooks on highway engineering, in professional papers, and it is set forth in the latest issue of the Asphalt Institute entitled "Asphalt Pocket Reference for Highway Engineers, 1937" by Prevost Hubbard, Chemical Engineer, and Bernard E. Gray, Chief Highway Engineer of the Asphalt Institute. This latter publication was specifically prepared for guidance of highway engineers in the science of design and construction of bituminous pavements. The chapter dealing with the Design of Asphalt Pavements is reproduced in full in Appendix A of this report.

One of the diagrams shown in the Asphalt Institute Reference Book is reproduced in Fig. 11. This diagram shows that for any given subgrade support a wheel load of 7500 pounds requires twice the thickness of pavement required for a 2000 pound wheel load. For example, Fig. 11 shows that if the subgrade support is 10 lbs. per square inch thickness required for a 2000-lb. wheel load is 5" and for a 7500-lb. wheel load it is 10"; similarly, for subgrade of 30 lbs. per square inch the relative thick-



THICKNESS OF PAVEMENT REQUIRED
FOR DIFFERENT WHEEL LOADS
WITH RELATION TO SUBGRADE SUPPORT
(Asphalt Institute Method)

Fig. 11

nesses of pavement are 2" and 4". This supports the square root relation, because when the load is quadrupled the thickness requirement is doubled. The square root of the wheel load relation is therefore substantiated and recommended for design by one of the leading authorities in the bituminous pavement field.

Square Root Relation in Design Formula for Flexible Types

The formula $t = \sqrt{\frac{W}{\pi s}} - e$ is advocated by the Asphalt Institute for the design of the thickness of flexible type pavements. This formula is also given in Fig. 10 together with a graphical representation of the assumptions upon which it is based. The terms have the following meaning:

t = thickness of pavement in inches

W = wheel load in pounds

s = bearing power of the subgrade in pounds per square inch

e = radius (in inches) of the circle over which the wheel load is assumed to be distributed.

This formula does not mathematically demonstrate that the thickness of a pavement varies directly as the square root of the wheel load, because there are two terms in the right-hand side of the equation; the first term obviously does vary as the square root of the wheel load (since π and s are constants for a given subgrade), but the second term ($-e$) is not under the square root sign. Actually, e which increases as the wheel load increases also varies about as the square root of the wheel load. For example, a wheel load of 2000 pounds requires a tire with a contact area of about 34 sq. in., which is equivalent to a circle of radius 3.3 inches. A wheel load of 7500 pounds requires an area of contact of about 79 sq. in. which is equivalent to a circle of radius 5.0 inches. In other words, when the wheel load is increased about four times the value of e does not quite double.

The above discussion is based upon single tires for both 2000 and 7500 pound wheel loads, which is consistent with the assumption in the formula that the load is distributed over a circle. If dual tires are used the formula does not hold unless the assumption is made that the dual areas can be converted into one single circular area. Bradbury* has derived equivalent circular areas for this purpose. He finds that for dual tires the radius of distribution for a 2000 pound load is 3.3 inches and for an 7500 pound load is 6.5 inches. In this case the increase in e is directly proportional to the square root of the wheel load.

Since e also varies substantially as the square root of the wheel load, then both terms on the right-hand side of the formula vary as the square root of the wheel load, and the application of the formula over the normal range of wheel loads will result in a thickness proportional to the square root of the wheel load.

Practice as well as theory has indicated very clearly that bituminous pavements must be made thicker if they are to be adequate for the heaviest motor vehicle than they have to be if only adequate for the basic vehicle, and practice also indicates quite clearly that the heaviest vehicles require pavements and subgrade which amount in a cost (including the more expensive stabilization of subgrade required for heavy traffic) to approximately twice as much for the heaviest truck as for the basic vehicle.

* Wheel Load Distribution, by R. D. Bradbury, 14th Proc. Highway Research Board.

Square Root Rule - Gravel and Earth Roads

The theories of distribution of stresses through bituminous pavement likewise apply to soils such as gravel, earth and clays, and lead to the same conclusion, namely, that the thickness required varies as the square root of the wheel load. The distribution of stresses in soils can also be obtained by Boussinesq's theory as demonstrated in Appendix B. This theory also leads to the squareroot relation, which is a further proof of the application of the square root of the wheel load theory to practically all kinds of soils as well as to pavement materials.

It is, therefore, reasonable to use the square root relation as a basis for determining the relative thicknesses required for different wheel loads for all kinds of pavements.

Does Annual Cost Vary as Square Root of Wheel Load?

Annual highway costs are computed from construction and maintenance expenditures. If the annual costs for highway facilities are to be considered proportional to the square root of the wheel load of the vehicles requiring these facilities, then it must be demonstrated that the elements of cost making up the annual cost vary on the whole as the square root of the wheel load, or if they do not, that there are other elements of cost of a more intangible nature which make up the deficiency.

The major elements of construction cost are for pavements and surfacing, grading, bridges and drainage structures. The cost of the pavement usually comprises most of the construction expenditure, especially in Ontario where little grading is required.

Generally speaking, a pavement of the same width and kind that is twice as thick as another will not cost twice as much to construct because some elements of cost vary with thickness and others do not. In the case of concrete pavements, a pavement twice as thick will probably cost 80% more than the thin one. For bituminous pavements 80% to 100% would be a fair ratio. For gravel roads the cost of a gravel layer twice as thick as another would cost twice as much; i.e., the increase in cost would be about 100%. These percentages apply to roads of the same type. The basic vehicle can be adequately served by a less expensive type of pavement than required for the heaviest vehicle.

Bituminous roads consisting of a blanket treatment, similar to surface treated water-bound macadam roads, or road mix and other thin bituminous concrete types are the usual pavements employed for roads having light traffic, and are therefore suitable for the basic road. The cost of such roads as these should be compared with the cost of the thickest concrete pavements required for the heaviest trucks in attempting to reach the ratio of the cost of the basic road to the cost of roads adequate for heaviest trucks. Such a comparison shows percentages of increase in cost exceeding 100%, i.e., in greater proportion than the square root relation.

In addition, there are other elements of costs made necessary for the heavy trucks which have not yet been considered. These are the additional width of pavement, the additional lanes required when the mixed traffic becomes considerable, and the fact that the heavy vehicle has destroyed many of the pavements, which were previously designed adequate for the lighter truck and the basic vehicle. Although these roads were designed with vision, it was impossible for engineers to prophesy the wheel loads the roads might be called upon to carry. Consequently, the capital expended in the past on highways which should have lasted many years has been dissipated by the destructive element of these heavy wheel loads.

Besides the additional thickness which increases the cost from 80% to 100% over the basic road, the additional width of pavement required by the wide commercial vehicle adds at least 10% to the width, and since this additional width is twice as thick as required for the basic pavement, the additional increase in cost is about 20%. The increased thickness and width, therefore, increases the cost from 100% to 120% above the cost of the basic pavement.

Additional lanes are also required on account of the presence of these wider and slower vehicles on heavy traffic roads. If all the vehicles were passenger cars, additional lanes now being built would not in many instances be required for several years. It is impossible to account for this added expense in such a manner as to charge it directly to the trucks, but it is a real and considerable cost attributable solely to the wide, slow moving trucks.

Grading costs (cuts and fills) increase materially with the width of the pavement; they also increase rapidly with a reduction in the gradient of the highway. Heavy vehicles benefit materially from reductions in the gradient and are, therefore, primarily responsible for a large part of the grading costs. We have no method of apportioning grading between heavy and light vehicles; in some cases the excavation necessary for making a road suitable for heavy trucks is at least twice that which would be required to make the same road

suitable for the basic vehicle, in other cases it is not. The grading cost is a small percentage of the annual cost in Ontario.

Bridges and drainage structures. The design of the bridge itself is dependent upon the wheel load; hence a bridge for heavy vehicles will cost more than one for light vehicles. Wider pavements require wider fills and longer culverts and wider bridges. The design of the bridge abutments may not be materially influenced by the wheel load. The cost of the abutments and piers, however, is greatly influenced by their size and height. Highway bridges are often made higher or longer to obtain flatter grades. In the case of grade separations they must be made much higher than required for basic vehicles in order to allow proper clearances for the larger trucks.

It is impossible to prove that in general the cost of all bridge structures are increased 100% (strictly 93%, since the factor used is 1.93) as between a bridge adequate for the basic vehicle and one adequate for the heaviest permissible truck, but it is perfectly clear that there is a very considerable increase in cost and that it may in some instances exceed 100%. The highway bridges in Ontario are infrequent and are mostly small structures and therefore represent a small percentage of the entire annual cost.

Maintenance costs will certainly be greater on concrete pavements and on bituminous pavements if the traffic includes heavy trucks and buses than if it is all

passenger cars, even though the pavements in both cases are properly designed for truck loads. The cost of maintenance is not proportional to the number of vehicles, but increases with their weight. It will be remembered that the square root of the wheel load ratio was approximately 1 to 2 in Ontario as between the heaviest vehicle in the assumed basic class and the heaviest truck, because the wheel load of the heaviest truck reaches the maximum permitted by law and this is nearly 4 times the wheel load of the heaviest vehicle in the basic class.

The effect of heavy trucks on the maintenance cost of pavements cannot as a practical matter be separated from other costs, but the effect of the heavier vehicles upon shoulder maintenance is marked and its cost can be separated. The shoulders are either of earth or gravel or, in a few instances, broken stone. On a gravel road, it is generally agreed that the maintenance cost is in proportion to the ton-mile, i.e., it will cost 8 times as much for the 8-ton vehicle to travel over the road than it will for a 1-ton vehicle. In Ontario the mileage of gravel roads is many times that of high type pavements, and the total maintenance cost per mile for a gravel road is generally higher than that for a high type pavement. A large proportion of the total annual maintenance is for gravel roads.

When one considers the fact that practically all the heavy trucks, and most trucks in fact, travel 4 to 10 times as many miles per year as the average passenger

car, it is obvious that, even if maintenance costs were distributed on the vehicle mile basis without any regard to the weight of the individual vehicle, the heavy trucks will be paying, not twice, but several times the amount the passenger car will pay because of the increased mileage.

We conclude that the relationship between cost of maintenance for the light and heavy vehicles is probably at least in proportion to the square root of the wheel load, i.e., that it is at least twice as much for the heaviest truck as for the passenger car.

We were unable to completely separate administration costs in this study, so we have included them with maintenance. We estimate that these costs are only about 4% of the annual cost, and since there are so many other items which will later be discussed in which the heavier vehicles have increased the annual cost, this item of administration is also allocated in accordance with the square root relation.

The above sets forth in general the basic reasons why the annual costs may be fairly assumed to be proportional to the square root of the wheel load. There are many other costs attributable to heavy trucks and buses that will later be discussed and which still further support this conclusion.

Application of the Square Root Method of Allocation of
Costs between Classes of Motor Vehicles

The square root method has been used to allocate annual highway costs in Table III. The classifications in Col. (1) were chosen to conform to weight classifications used for licensing purposes in Ontario. The basic group, Class I, includes passenger cars, motor cycles, trailers under 1 ton and light delivery and farm trucks under 2 tons gross weight. Class II includes the next heavier class of trucks and buses, 2 to 3 tons gross weight; Class III, the 3 to 4 ton group; and so on up to Class X. Five licensing classes between 10 and 15 tons gross weight are included in Class X; these classes are grouped because all vehicles in these classes probably require the maximum allowable wheel load of 7500 pounds. This is the heaviest wheel load, therefore, for which allocation of costs need be made.

Col. 2. - The average gross weights for each class are shown in Col. (2). The basic class includes vehicles of widely varying weight. The average gross weight of a passenger car and two passengers is taken as 3400 pounds, which is a liberal weight considering the fact that the light coach or sedan weighs empty about 2800 pounds. Some passenger cars weigh up to 5000 pounds, but they are very few in number. The trailers in Class I are licensed for weights up to 1 ton. They are probably small two-wheel trailers attached behind passenger cars

TABLE III

ALLOCATION OF ANNUAL HIGHWAY COST AMONG DIFFERENT CLASSES OF MOTOR VEHICLES - PROVINCE OF ONTARIO - YEAR 1936

SQUARE ROOT OF WHEEL LOAD METHOD

Classification	Average Licensed Gross Weight	Wheel Load	Kind of Vehicle	Number Registered in 1936	Total Class Registration	Number Requiring Increment of Annual Cost (10)	Highway Cost Index	Increments of Cost Index	Increments of Annual Cost Chargeable to Each Class	Increment of Annual Cost per Vehicle (10) + (7)	Total Payment Required per Vehicle	Portion of Annual Costs Contributed by Each Class (12) x (8)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Basic	3,400 400 1,000 4,000 "	2,000 (Assumed for Classes I & II)	Passenger Cars Motor Cycles Trailers Farm Trucks Delivery Trucks Trailers	514,211 4,553 24,270 8,355 19,494 868			(Proportional to square root of Wheel Load)		\$	\$	\$	\$
I A B D	5,000		Farm Trucks Delivery Trucks Trailers Busses	4,676 10,310 299 16								
II					587,652	618,054	1.00	1.00	28,280,000	42.52	42.52	24,987,000
III	7,000	2,625	Farm Trucks Other Trucks Trailers Busses	2,480 5,765 221 30								
					8,516	30,402	1.15	.15	3,942,000	129.66	172.18	1,466,000
IV	9,000	3,375	Trucks Trailers Busses	5,146 356 72								
					5,574	21,886	1.20	.15	3,942,000	180.12	252.30	1,964,000
V	11,000	4,125	Trucks Trailers Busses	3,029 332 114								
					3,475	16,312	1.44	.14	3,679,000	225.54	577.84	2,008,000
VI	13,000	4,875	Trucks Trailers Busses	2,636 394 75								
					3,105	12,827	1.56	.12	3,154,000	245.70	625.54	2,557,000
VII	15,000	5,625	Trucks (General) " (Municipal) Trailers (General) " (Municipal) Busses	2,675 3,065 707 373 94								
					6,964	9,732	1.68	.12	3,154,000	324.06	1,147.62	7,958,000
VIII	17,000	6,375	Trucks Trailers Busses	692 17 40								
					949	2,796	1.78	.10	2,828,000	939.24	2,086.86	1,980,000
IX	19,000	7,125	Trucks Trailers Busses	1,328 80 97								
					1,505	1,849	1.88	.11	2,881,000	1,563.55	3,650.41	5,494,000
X	21,000 to 29,000 (Av. 22,700)	7,500	Trucks Trailers Busses	202 13 129								
					344	344	1.93	.04	1,051,000	3,055.23	6,705.64	2,307,000
Total								1.93	50,721,000	6,705.64		50,721,000
			Foreign Cars						804,000			804,000
Grand Total				618,054	618,054				51,525,000			51,525,000

for carrying camping equipment or agricultural products; they are entered at 1000 pounds, i.e., one-half their maximum licensed weight. The light delivery trucks in Class I are licensed up to 2 tons gross weight and probably weigh about this amount with load, so we have assigned to them a weight of 4000 pounds. In the other classes, except Class X, the gross weight used is half-way between the license group limits, i.e., trucks licensed between 2 and 3 tons gross are assumed to weigh 5000 pounds.

Col. 3. - The wheel load assumed for Classes I and II (Col. 3) is 2000 pounds. This is a proper wheel load for vehicles in Class II, but is obviously much heavier than would be typical for Class I. The wheel load of the basic class would probably not exceed 1200 pounds. Considering, however, that roads for the basic vehicle would in the interest of good practice be built sufficiently thick to accomodate a wheel load of 2000 pounds, we have included Classes I and II in one wheel load group. If a 1200-pound wheel load had been used for the basic class, the charge for a passenger car in Table III would be about \$10 less and that for the heaviest truck about \$1000 greater than the Table shows. The adoption of a 2000 pound wheel load for the basic class is a very definite advantage to the heavy vehicles at the expense of the passenger car and light truck of equivalent weight. In Classes III to IX inclusive, the wheel load is assumed

to be $37\frac{1}{3}\%$ of the average licensed gross weight which represents the proportion of gross weight found on a rear wheel when the truck has its licensed load. Class X has the maximum allowable wheel load of 7500 pounds.

It will be noticed that the square root method of allocation is based upon total licensed gross weights and their corresponding wheel loads, and not upon average loaded weights which depend upon the extent to which the truck is loaded. This is a proper procedure since the square root method allocates the cost of facilities required which are dependent upon the design wheel load which must be based upon total allowable gross weight in each class. In the ton-mile method of allocation, later described, the average loaded weight is used, since the loaded weight is the measure of use rather than the maximum allowable weight.

Col. 4. - Farm trucks in Col. (4) have been kept separate from other trucks because of the limited use which they make of the highways which enters into ton-mile considerations but does not effect Table III values. Farm trucks are assumed to be 30% of the total registration in the first three classes. No information is available in Ontario as to the exact number of farm trucks. In Quebec, where farm trucks have a special license, they comprise about 30% of the registration.

Municipal trucks are not classified by weight in Ontario. We have assumed that they average about 7.5 tons gross weight, based upon the best information available.

There is no separate Department record kept of semi-trailers and trailers and of trucks and tractor trucks in Ontario; semi-trailers and trailers are classified as "trailers" and trucks and tractor trucks are called "trucks". Some of the trucks in the heavier groups are doubtless tractors but we have no way of identifying them. Tractors are licensed for gross weights which include the weight of the front end of the semi-trailer which they support. This places the tractors in a weight class comparable with trucks of the same type. Most of the trailers in the heavier classes are probably semi-trailers, since the length limitation is now 50 ft.

An item of foreign cars is included because vehicles registered outside of Ontario and particularly in the States purchase gasoline in Ontario and thereby contribute to motor vehicle revenue. It will later be shown in Table IV that these foreign cars contribute about \$804,000 in revenue. This has been deducted from \$51,525,000, the total annual rural road and urban street costs for 1936, giving \$50,721,000 to be allocated to Ontario vehicles.

Col. 5. - The numbers of passenger cars and of trucks and trailers registered in the different classes (Col. 5) were furnished by the Motor Vehicles Branch of the Department of Highways in an answer to a questionnaire. The Vehicles Branch did not furnish us with weight

classifications for buses; the distribution shown in Col. (5) is based upon the number paying the fees required for the different weight classes as published in Ontario Department of Highways Annual report for 1936. No division has been made between public and private commercial vehicles. The nature of the business of the truck does not directly influence the cost of highway facilities; it may, however, be taken into account in levying fees against motor vehicles because of special privileges and use which they enjoy on the public highway.

Cols. 6 and 7. - The number of vehicles registered in each class is given in Col. (6) and the number requiring each increment of annual cost is given in Col. (7). Note that all vehicles (618,054) require the first increment, i.e., the cost for the basic road. The second increment of cost (for Class III) is required only by those vehicles heavier than Classes I and II, i.e., 618,054 less 587,652; the third increment (for Class IV) is required by 30,402 less 8,516, and so on class by class until only 344 vehicles are left which require facilities for the maximum wheel load of 7500 pounds.

Col. 8. - The highway cost indices in Col. (8) are ratios of the square roots of the wheel loads in Col. (3). The 2000 pound wheel load is called index 1.00. The index for class 3 wheel load is 1.00 times the square root of 2625 divided by the square root of 2000 = 1.15, and so on until the 7500 pound wheel load is reached

which has a square root ratio of 1.93 with respect to the 2000 pound wheel load.

Cols. 9 and 10. - Col.(9) shows the differences between cost indices, i.e., the increments of cost index between classes. These are used for determining the increments of annual cost in Col. (10) as follows: The total annual costs to be allocated, \$50,721,000, is first divided by 1.93, the total of all increments. This quotient is then multiplied by the increment of cost for each class in Col. (9), giving the corresponding increments of annual cost in Col. (10).

Cols. 11, 12 and 13. - The increment of annual cost to be paid per vehicle registered in each class is found by dividing the cost increment in Col. (10) by the number registered in Col. (6). These amounts are shown in Col. (11). With the exception of Class I, these amounts are only increments of the total payment required from each vehicle, therefore, they must be added accumulatively, giving the total payments per vehicle in each class as shown in Col. (12). The final distribution of the total annual cost \$50,721,000 among all classes is made in Col. (13) by multiplying the payments in Col. (12) by the number of vehicles registered in each class in Col. (6).

The annual charge for basic vehicles derived in Col. (11) is \$42.52. At present passenger cars pay about \$26 in fees and gasoline tax, and light delivery

trucks pay about \$37. Therefore, a charge of \$42.52 would represent a substantial increase for passenger cars and a small increase for the light trucks. As the annual cost chargeable to motor vehicles (\$50,721,000) is about twice the present total revenue from motor vehicles, an increase in charges is to be expected. The charges against the heavier vehicles are increased in greater proportion than for basic vehicles, reaching a maximum charge of \$6706 for the heaviest truck in Class X. The high charges in the heavier classes result from the fact that there are so few of these vehicles to share their increments of annual cost. If these heavier vehicles, say Classes VIII to X, were actually assessed the full amount of the charge found in Table III, they would probably be unable to operate at a profit, and would be driven off the road. This might prove to be in the public interest, since a large saving could be realized in annual cost, because it would be unnecessary in the future to provide these last increments of cost, amounting to \$6,570,000 annually for 2798 vehicles, which is 0.4% of the total registration. The larger and heavier units could be allowed to operate for a reasonable period, and then their owners would be obliged to replace them with lighter equipment.

If the present wheel load limitations are not reduced, and if the heavier vehicles are allowed to operate for fees substantially less than the charges derived in Table III, then the fact must be faced that these heavier vehicles are being subsidized by the lighter vehicle users, who must pay a large share of the cost for

highway facilities in excess of those adequate for their own requirements. If the cost of these extra facilities is not charged against the lighter vehicles, then it must be borne by the general public through other forms of taxation. It cannot be escaped.

As previously stated the square root or increment method is deficient in that it allocates only the cost of facilities and does not take into account the use made of the facilities. It results in a uniform charge for all the vehicles in each weight class, irrespective of the use made of highway facilities by the different vehicles within each group; annual mileages do not enter into the method. In Ontario passenger cars probably travel on the average from 6000 to 6500 miles per year. There are no mileage statistics available for passenger cars in Ontario, but in several of the States an average annual mileage of 7000 has been found. Annual mileages in Ontario will probably be less than in the States on account of less travel during the winter months. Motor buses and heavy trucks, on the other hand, travel anywhere from 20,000 to 60,000 miles per year; i.e., they travel from 3 to 10 times the mileage of the average basic vehicle. These facts do not enter into consideration in the square root of the wheel load method.

We have considered two other modifications of the square root method, combining it with the ton-mile method of allocation. Before presenting these methods, the straight ton-mile method and its weakness will be discussed.

Straight Ton-Mile Basis for Allocation of Costs

The ton-mile is the product of the tons and the miles over which it is moved. It is obviously a simple and direct method of measuring commercial highway use, but it likewise has certain weaknesses. The straight ton-mile method involves estimating the average ton-miles for each vehicle type. The grand total of all ton-miles is then divided into the total annual cost to be allocated giving a flat rate of charge per ton-mile for all vehicles. This flat ton-mile rate multiplied by the ton-miles for each vehicle gives the respective charges against each vehicle, and when applied to all vehicles will yield the total annual cost. We have called this method the straight ton-mile method in order to distinguish it from a method later described in which the ton-mile rate varies.

Although the straight ton-mile method allocates in proportion to use made of the highways, it does not adequately charge the heavy vehicles for the extra facilities required for them. It results in excessive charges for passenger cars and light trucks, and insufficient charges against the heavier vehicles. It would increase the present registration fee for passenger cars from about \$5 to \$44, and the total charge including gas tax from \$26 to \$65.

If all the tons carried over the highways were passenger cars and light trucks, then the annual cost of highways would be about half what they are today, as shown in Table III. In fact, these heavier vehicles contribute so small a part of their fairshare, on the ton-mile basis, that the basic class is called upon to contribute much more than its fair share of the cost of facilities. The straight ton-mile basis is so unfair to the basic vehicle that we have not used it.

Combined Square Root and Ton-Mile Method of Allocation

Although the straight ton-mile method alone is not a fair method of allocation, it may be used to advantage to allocate costs among vehicles requiring the same facilities; that is, it may be used in connection with the square root method to allocate the cost of facilities to the different vehicles within each class. A combination of the square root and the ton-mile methods will charge the individual vehicles more nearly in proportion to both facilities and use, particularly in Classes I and II which includes vehicles of widely different weights and mileages.

The combined square root and ton-mile method is shown in Table IV. Before proceeding with the allocation, it is first necessary to select average mileages and vehicle weights so as to develop representative values of ton-mile use for each type of vehicle.

The classification groups and all items in Cols. (1) to (5) inclusive are the same as in Table III. The average mileages assumed for each type of vehicle are given in Col. (6). In the absence of mileage statistics in Ontario, we have assigned what we believe to be reasonable mileages, based upon experience in the States, and more particularly the mileages compiled by the U.S. Bureau of Public Roads in estimating revenue from gasoline tax.* The adopted mileages are consistent with

* Taxation of Motor Vehicles - 1932.

TABLE IV
ALLOCATION OF ANNUAL HIGHWAY COST AMONG DIFFERENT CLASSES OF MOTOR VEHICLES - PROVINCE OF ONTARIO - YEAR 1966
COMBINED SQUARE FOOT AND TON-MILE METHOD

ALLOCATION TO CLASSES BY SQUARE FOOT METHOD AND WITHIN CLASSES ON TON-MILE BASIS

Classification	Average Licensed Gross Weight	Wheel Load	Kind of Vehicle	Number Registered in 1966	Average Annual Mileage Per Vehicle	Estimated Miles per Imperial Gallon of Gasoline	Gallons of Gasoline Per Vehicle (6) x (7)	Gallons of Gasoline Used By All Vehicles in 1966 (8) x (8)	Average Weight (Tons) (9) x (10)	Ton-Miles Per Vehicle Per Year (9) x (11)	Gross Ton-Miles All Vehicles in Each Class (11) x (5) (Thousands)	Total Ton-Miles Per Class from Col. (12) (Thousands)	Portion of Total Annual Cost Assigned to Each Class By Square Foot Method	Ton-Mile Rate for Each Class (14) x (15)	Annual Cost Assigned to All Vehicles of Each Kind in Each Class (15) x (16)	Charge Per Vehicle (15) x (17)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
Basic	3,400	2,000	Passenger Cars	514,511	6,300	18	350	179,970	1.70	10,710	5,507,970					
I	400	(Assumed)	Motor Cycles	4,538	5,500	50	70	819	.20	700	1,887					
A	1,000	For Classes 1 & II	Trailers	564,970	4,000	-	-	-	.50	1,800	36,405					
B	5,000		Farm Trucks	8,355	4,000	16	250	2,090	1.75	7,000	56,485					
II			Delivery Trucks	19,484	8,000	16	500	9,747	1.75	14,000	272,518					
			Trailers	868	4,000	-	-	-	1.48	5,850	5,078					
			Farm Trucks	4,876	5,000	14	257	1,669	2.14	10,700	50,033					
			Delivery Trucks	10,810	10,000	14	714	7,790	2.14	21,400	235,474					
			Trailers	599	4,000	-	-	-	1.82	7,390	5,207					
			Busses	18	12,000	14	858	-	2.27	27,250	456					
												6,189,451	24,987,900	0.0040501		
III	7,000	2,625	Farm Trucks	2,480	5,000	12	417	1,034	2.82	14,800	53,216					
			Other Trucks	5,785	15,000	12	1,000	5,785	2.82	33,350	195,882					
			Trailers	221	5,000	-	-	-	2.53	15,650	2,796					
			Busses	30	14,000	12	1,167	-	3.18	44,500	1,335					
												225,169	1,466,000	0.0062338		
IV	9,000	3,375	Farm Trucks	5,146	14,000	10	1,400	7,204	3.64	50,900	261,951					
			Trailers	356	8,000	-	-	-	3.28	26,100	4,292					
			Busses	72	16,000	10	1,600	-	3.96	63,400	4,565					
												275,788	1,864,000	0.0071214		
V	11,000	4,125	Trucks	3,029	16,000	9	1,778	5,396	4.46	71,400	216,871					
			Trailers	285	16,000	9	2,222	-	4.04	84,600	21,447					
			Busses	114	20,000	-	-	-	4.82	96,400	10,980					
												248,708	2,006,000	0.0080737		
VI	13,000	4,875	Trucks	2,636	18,000	8	2,250	5,801	5.26	94,680	245,578					
			Trailers	394	18,000	-	-	-	4.86	87,480	34,467					
			Busses	75	24,000	8	3,000	-	5.86	135,640	10,188					
												294,251	2,557,000	0.0086904		
VII	15,000	5,855	Trucks (General)	2,676	20,000	7.5	2,667	7,143	6.04	120,800	325,140					
			Trailers (Municipal)	5,085	10,000	7.5	1,533	4,111	6.04	60,400	196,354					
			Trucks (General)	707	20,000	-	-	-	5.63	116,600	79,608					
			Trailers (Municipal)	373	8,000	-	-	-	5.83	45,400	16,934					
			Busses	94	28,000	7.5	3,732	-	6.81	186,280	17,154					
												823,150	7,958,000	0.0127706		
VIII	17,000	6,375	Trucks	892	22,000	7.0	3,143	2,804	6.84	150,480	134,228					
			Trailers	17	22,000	-	-	-	6.88	140,580	2,288					
			Busses	40	28,000	7.0	4,571	-	7.33	224,560	9,368					
												145,996	1,980,000	0.0125650		
IX	19,000	7,125	Trucks	1,328	24,000	6.5	3,628	4,903	7.99	182,160	241,909					
			Trailers	80	24,000	-	-	-	7.14	171,360	15,709					
			Busses	97	36,000	6.5	5,538	-	8.20	296,800	29,634					
												284,252	5,494,000	0.0193279		
X	21,000 to 29,000 (Av. 25,000)	7,500	Trucks	808	26,000	6.0	4,838	875	8.99	233,740	47,216					
			Trailers	12	26,000	-	-	-	8.54	222,040	2,887					
			Busses	129	40,000	6.0	6,867	-	9.78	391,000	50,465					
												100,548	2,207,000	0.0229397		
Total			Foreign Cars					249,354			8,277,285	8,277,285	50,721,000			
								12,399					804,000			
Grand Total				618,054				269,753 (Thousands)			8,277,285 (Thousands)	8,277,285 (Thousands)	51,525,000		51,525,000	

the gasoline consumed by Ontario and "foreign" cars, that is, all the gasoline consumed in Ontario is accounted for, as shown in Col. (9).

The rates of gasoline consumption in Col. (7) are based upon a study of published records of gasoline consumption in the States, particularly those compiled by General Motors Corporation, and those used by U.S. Bureau of Public Roads.* The rates of consumption were converted from U.S. gallons into Imperial gallons, so as to apply to the Ontario problem.

The gallons of gasoline used per year by each vehicle type is shown in Col. (8). This was found by dividing the annual mileage, Col. (6), by the rate of gasoline consumption in Col. (7). The total gallons of gasoline used by all vehicles of each type is given in Col. (9). It is Col. (8) multiplied by Col. (5).

It is a well established fact that Ontario roads are used by cars from the States to a greater extent than Ontario cars use roads in the States. If the interchange of cars was about equal, then the presence of these "foreign" cars might be overlooked, since they would contribute about as much in gasoline tax to the Province as Ontario cars contribute to the States. Entry statistics show, however, that many more cars enter the Province for touring purposes, than leave the Province. Cars which enter for only a few hours probably buy no gasoline in the Province, but those which stay over 2 days probably

* Taxation of Motor Vehicles - 1932.

do buy gasoline in Ontario and thereby contribute to motor vehicle revenue through the gasoline tax. From a study of entry statistics and traffic counts, we have estimated that foreign cars consume about 13,400,000 gallons of gasoline per year as shown at the bottom of Col. (9). At the tax rate of 6 cents a gallon, this consumption represents a contribution of \$804,000 towards the support of Ontario highways by foreign cars. We have deducted this amount from the total annual cost of roads and streets and allocated the balance to Ontario vehicles.

The average loaded weight of trucks, trailers and buses (Col. 10) is taken as their empty weight plus 55% of the allowable load. This percentage was shown in certain actual load measurements for trucks made by the Ontario Department of Highways. No load reduction was made for passenger cars and trailers in Class I. The empty weight of trucks, trailers and buses was based upon a study of statistics compiled by U.S. Bureau of Public Roads in the "Taxation of Motor Vehicles - 1932".

The ton-miles per vehicle in Col. (11) is the product of the annual mileage in Col. (6) and the average loaded weight in Col. (10). The gross ton-miles for all vehicles of each type and class is given in Col. (12). It is the product of Cols. (11) and (5). The ton-mile values in Cols. (11) and (12) are used in all subsequent methods of allocation involving the ton-mile unit.

The respective portions of annual cost chargeable

to each class by the square root method were determined in Col. (13) of Table III. These amounts have been transferred to Col. (14) of Table IV. The total ton-miles in each class to which these costs apply are shown in Col. (13). The costs in Col. (14) divided by the ton-miles in Col. (13) established the ton-mile rate of charge for each class shown in Col. (15). The portions of annual cost chargeable to all vehicles of each kind in each class are shown in Col. (16), and the charge per vehicle of each kind and class is shown in Col. (17).

It will be noticed that this method of allocation (Table IV) does not change the amount of annual cost assigned by the square root method to each class, but it does distribute the assigned costs among the vehicles in each class in proportion to use rather than in proportion to number (as in Table III).

Referring to Col. (17), the charges per vehicle in the basic class are \$2.84 for a motor cycle, \$43.38 for a passenger car and \$110.36 for a bus. These charges are much more reasonable than a flat rate of \$42.52 for all basic vehicles as was obtained in Table III. In any of the heavier classes the buses are charged more than the trucks and trailers because they have higher annual mileages; that is, the trucks pay less and the buses more than the charge derived by the straight square root method. This modification of the square root method results in a more equitable schedule of charges against the vehicles within

each class. The amount to be allocated within each class, however, is still dependent upon the number of vehicles registered in that class, which is one of the criticisms of the square root method. This method does not, therefore, correct this characteristic of the square root method.

Ton-Mile Basis with Increasing Ton-Mile Rate

In order to overcome the objections to the combined square root and ton-mile methods of Table IV, we have combined them in still another way. In this new method the facilities required by the basic class are determined by the square root method, Table III, and \$24,987,000 is allocated among these basic vehicles on the ton-mile basis just as was done in Table IV; and the balance ($\$50,721,000 - \$24,987,000 = \$25,734,000$) representing the total charges against the heavier vehicles, Class III to X, is then allocated on a ton-mile basis with a uniformly increasing ton-mile rate per class such as will produce the \$25,734,000.

The method of allocation is shown in Table V. The classification groups and all items in Cols. (1) to (12) are the same as in Table IV. These columns are described above in connection with Table IV.

The ton-mile rate for basic vehicles in Col. (13) is the same as in Col. (15) of Table IV. It was obtained by dividing the basic vehicle's portion of annual cost in Table III, Col. (13) by the total ton-miles in the basic class, Col. (14), Table IV.

TABLE V
ALLOCATION OF ANNUAL HIGHWAY COST AMONG DIFFERENT CLASSES OF MOTOR VEHICLES - PROVINCE OF ONTARIO - YEAR 1956
INCREASING TON-MILE RATE METHOD WITH CHARGE FOR BASIC CLASS DETERMINED BY SQUARE ROOT METHOD

Classification	Average Licensed Gross Weight	Wheel Load	Kind of Vehicle	Number Registered in 1956	Average Annual Mileage Per Vehicle	Estimated Miles per Imperial Gallon of Gasoline	Gallons of Gasoline Per Vehicle Per Year (6) x (7)	Gallons of Gasoline Used By all Vehicles in 1956 (6) x (5) (Thousands)	Average Loaded Tons (8) x (10)	Ton-Miles Per Vehicle Per Year (6) x (10)	Gross Ton-Miles All Vehicles in Each Class (11) x (5) (Thousands)	Uniformly Increasing Ton-Mile Rate to Yield \$50,721,000	Allocation of \$50,721,000 to all Classes at Uniformly Increasing Ton-Mile Rate (12) x (13)	Charge Per Vehicle (11) x (13) 1956	Estimated Present Payments Fees, Oct. 1, and Seat Tax (Buses) Rates 1956	Estimated Present Payments Fees, Oct. 1, and Seat Tax (Buses) Rates 1956
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
Basic I A B C D	2,400 400 1,000 4,000 "	2,000 (Assumed for Classes I & II)	Passenger Cars Motor Cycles Trailers Farm Trucks Delivery Trucks Trailers	514,811 4,558 24,270 6,358 19,494 968	6,200 3,500 5,000 4,000 8,000 4,000	18 50 - - 16 -	260 70 - 250 500 -	179,970 519 150 2,090 8,747 1,46	1.70 1.70 1.50 1.75 1.75 1.46	10,710 700 1,500 7,000 14,000 5,850	5,507,200 3,187 36,405 58,498 272,816 5,078	\$0.0040501*	\$22,305,000 15,000 147,000 297,000 1,105,000 20,000	\$ 43.38 8.94 6.08 29.35 56.70 23.69	\$ 31 7 5 23 40 10	\$ 26 5 2 23 37 8
	5,000		Farm Trucks Delivery Trucks Trailers Buses	4,678 10,910 999 16	5,000 10,000 8,000 12,000	14 14 14 14	357 714 790 868	1,668 7,790 1.82 14	2.14 2.14 1.82 2.77	10,700 21,400 7,380 27,520	50,035 235,474 2,207 456		203,000 946,000 9,000 2,000	43.34 86.67 29.69 110.86	45 87 21 115	39 61 16 108
	7,000	2,825	Farm Trucks Other Trucks Trailers Buses	2,480 5,785 221 20	5,000 12,000 5,000 14,000	12 12 12 12	417 1,000 5,785 1,167	1,024 5,785 2.53 25	2.82 3.18 2.53 3.18	14,800 35,850 12,850 44,500	35,216 195,822 2,796 1,335	0.0058185	205,000 1,139,000 16,000 8,000	88.62 196.96 73.60 258.92	73 108 35 171	61 96 24 162
	9,000	3,375	Trucks Trailers Buses	5,148 356 72	14,000 8,000 16,000	10 10 10	1,400 1,600 -	7,204 115 -	3.64 3.28 3.96	50,900 28,100 85,400	261,821 9,292 4,565	0.0075868	1,967,000 70,000 35,000	366.17 198.02 461.00	149 50 206	132 88 222
V	11,000	4,125	Trucks Trailers Buses	5,028 533 114	16,000 16,000 20,000	9 9 9	1,778 - 2,222	5,586 - 253	4.46 4.04 4.82	71,400 84,600 96,400	216,271 21,447 10,990	0.0093552	3,023,000 201,000 102,000	667.96 804.85 901.84	191 66 339	170 50 350
	13,000	4,875	Trucks Trailers Buses	2,836 394 78	18,000 18,000 24,000	8 8 8	2,250 - 5,000	5,931 - 225	5.28 4.86 5.66	94,880 87,480 185,840	249,578 34,467 10,168	0.0111258	2,776,000 385,000 115,000	1,055.18 975.09 1,511.02	233 77 464	208 58 443
VII	15,000	5,825	Trucks (General) " (Municipal) Trailers (General) " (Municipal) Buses	2,875 5,085 707 878 94	20,000 10,000 20,000 8,000 28,000	7.5 7.5 - - 7.5	2,667 1,333 - - 3,755	7,143 4,111 - - 851	6.04 6.04 5.83 5.83 6.51	120,800 80,400 115,800 45,400 128,290	325,140 186,334 79,008 18,934 17,154	0.0138918	4,186,000 2,402,000 1,056,000 218,000 221,000	1,557.35 776.87 1,451.63 585.29 824.96	272 88 86 2 300	244 82 66 2 576
VIII	17,000	6,375	Trucks Trailers Buses	892 17 40	22,000 22,000 28,000	7.0 7.0 7.0	3,143 - 4,071	2,804 - 4,071	6.84 6.82 7.33	150,480 140,360 224,560	134,228 2,288 9,366	0.0146603	1,968,000 85,000 127,000	2,206.09 2,057.72 2,438.72	633 108 764	577 81 724
IX	19,000	7,125	Trucks Trailers Buses	1,328 80 97	24,000 24,000 36,000	6.5 6.5 6.5	3,692 - 5,538	4,903 - 537	7.59 7.14 8.54	182,160 171,280 222,040	241,909 13,709 28,634	0.0164287	3,974,000 225,000 470,000	2,992.65 2,815.22 4,948.75	592 120 942	349 90 809
X	21,000 to 25,000 (Av. 22,700)	7,500	Trucks Trailers Buses	802 13 129	28,000 28,000 40,000	6.0 6.0 6.0	4,833 - 6,667	875 - 860	8.99 8.54 9.78	233,740 222,040 391,800	47,216 2,687 50,465	0.0181971	869,000 54,000 918,000	4,155.26 4,040.48 7,118.69	486 163 1,180	451 158 1,185
Total								249,324			8,277,285		50,721,000			
			Foreign Cars					13,899			8,277,285		50,721,000			
Grand Total				618,054				862,728 (Thousands)			8,277,285 (Thousands)		51,525,000			

* Ton-mile rate for basic class was taken from Col. (15) of Table IV, the combined square root and ton-mile method. It gives substantially the same charge per passenger car as derived by the square root method, Table III, i.e., about \$43.

* Seat tax for buses was estimated on the assumption that one-quarter of the bus mileage is on County Roads at 1/50 cent per seat-mile, one-half on King's Highways at 1/50 cent per seat-mile, and the rest on urban streets for which no seat tax is charged.

Beginning with Class III, the ton-mile rate is increased between classes by equal increments of \$0.0017684 to a maximum rate per ton-mile of \$0.018197 for Class X, thus producing a graduated scale of ton-mile rates (Col. (13)) that will yield a total charge from all vehicles of \$50,721,000. This scale of ton-mile rates is lower for the heavier classes than that found for the combined square root and ton-mile method in Table IV, Col. (15). To satisfy the square root method, the ton-mile rates should have been increased in Table V in an ascending scale rather than uniformly; however, for simplicity and uniformity we have adopted the uniformly increasing scale. This definitely favors the heavier vehicles. For example, the heaviest truck in Class X is charged \$4253 in Table V compared with \$6706 by the square root method in Table III and \$5362 in Table IV. This method tends, therefore, to subsidize the heaviest trucks and buses at the expense of the light and intermediate weight types. The method has the advantage, however, of producing a regular and uniform schedule of rates and charges which is not influenced by the numbers of vehicles registered in each class, except to the extent that an increase in the number of vehicles in any class will reduce the charges to all classes. The method is reasonable and practical, since it takes into account both use and the cost of facilities required throughout the entire range of vehicle classifications. The charges against all classes (including the passenger

car) are raised above present actual charges; the heavier vehicles are raised much more than the lighter vehicles.

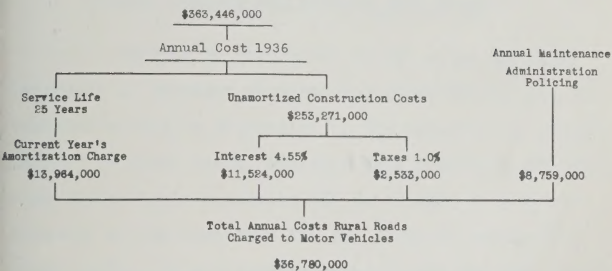
The estimated actual payments by vehicles in each class are shown for 1936 in Col. (16) and for 1938 (after fee reductions) in Col. (17). The buses pay a seat tax in addition to the gasoline tax and registration fee. The amount of the seat tax has been estimated and included with fees and gasoline taxes in Cols. (16) and (17).

Of the different methods of allocation discussed in their report we recommend the adoption of the results of Table V.

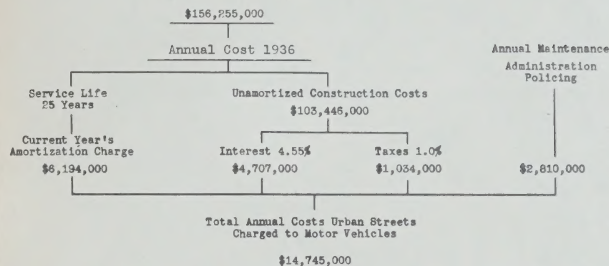
The summary of the entire procedure and results reached by the method of Table V are shown in the following chart.

RURAL ROADS

King's Highways - County Roads - Township Roads
Aggregate Construction Expenditures 1918-36

URBAN STREETS

Aggregate Construction Expenditures 1918-36
(Excluding Sidewalks and Lighting)



Total Cost Charged to Motor Vehicles
\$51,525,000

Foreign Cars
\$804,000

Ontario Vehicles
\$50,721,000

Classification	I	II	III	IV	V	VI	VII	VIII	IX	X	
Licensed Gross Weight	Pass. Cars	Under 2 Tons	2-3 Tons	3-4 Tons	4-5 Tons	5-6 Tons	6-7 Tons	7-8 Tons	8-9 Tons	9-10 Tons	Over 10 Tons
Charge per Vehicle*	\$43	\$57	\$87	\$197	\$386	\$688	\$1,053	\$1,557	\$2,206	\$2,993	\$4,253
Present Payments - 1938	26	37	61	96	132	170	208	244	297	349	431

* These charges are for Passenger Cars and Trucks - See Table V for Complete Allocation.

Other Elements of Highway Cost Incurred for the Heavier Commercial Vehicles - Advantages Enjoyed by the Trucks - Delays and Hazards they Cause.

Earlier in the report it was shown that the thickness of pavement required for different weights of vehicles varies in proportion to the square root of their respective wheel loads, and that this increased the thickness of the basic pavements 93% to provide an adequate pavement of the same type for the heaviest permissible wheel loads. It was admitted that it did not follow that all of the elements of annual highway cost would be increased 93% to provide for the heavy vehicles. It was further pointed out that by far the largest part of the annual cost, namely, the pavement would increase in cost nearly as its thickness increased, and that when the cost of additional width of pavement required for the wide vehicles was evaluated it was fully true that the pavement costs as a whole would increase at least 93%. It was further shown that the basic vehicle does not require a concrete pavement and that the ratio of 1 to 1.93 is therefore more than justified as regards the relative cost of pavements. Maintenance depends upon the vehicle weight, the number of passages it makes, and upon several other less important characteristics. It is difficult to evaluate these costs between vehicles. Administration costs which amount to but 3% of the total cost probably

do not follow the square root rule.

In addition to these major items of cost there are several other elements in highway costs which are special benefits to the commercial vehicle. The latter have deprived the passenger car user from a free use of the basic highway; it delays the passenger car; it introduces hazards; it occupies the road for longer periods of time and space. These are costly to the passenger car user.

The following items causing additional cost will now be discussed in more detail; earlier in the report they were briefly mentioned.

Additional width of pavements and shoulders

Additional traffic lanes

Additional maintenance of road surfaces and
shoulders

Shortened life of existing pavements.

The heavier vehicles also enjoy certain advantages in the use of highways which are not shared by other vehicles. Their presence on the highway often causes delays and hazards to other traffic. Some of these items now to be discussed are:

Nuisance, delays and hazards to other traffic

Special benefits from road improvements such
as flatter gradients, additional lanes,
smoother pavements

Relative occupancy of trucks and passenger cars

Use of highways as a place of business.

Although these additional facilities and special benefits to the heavier vehicle are not easily evaluated, they are very real benefits and should be considered in determining the proper charge for the use of the roads.

Additional Width of Pavements and Shoulders

The maximum width of vehicle allowed on Ontario highways is 8 feet. Passenger cars are slightly less than 6 feet wide. Although there is no definite relationship between weight and width, it is generally true that width increases with weight. The heaviest trucks and buses are nearly always built to the maximum legal width. From a physical standpoint the truck and the bus are obviously the limiting vehicles in determining the minimum width of a traffic lane. The narrowest pavement upon which they can barely pass with almost no clearance between them is 18 feet, which is evidently not adequate.

Studies of the transverse distribution of traffic* show that most of the right wheel passages on an 18-foot pavement lie between 2 and 4 feet from the edge of the pavement when no car is passing in the opposite direction. When two cars pass in the opposite direction the passenger cars run about 1 foot nearer the edge. From these observations it may be deduced that the passenger car driver's preferred position brings his right wheel

* Public Roads, March 1929, September 1937

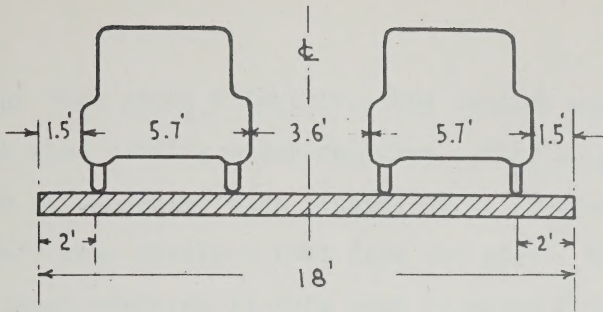


Fig. 12 Two Passenger Cars Passing on an 18 Foot Pavement with Right Wheels 2 Feet from Edge

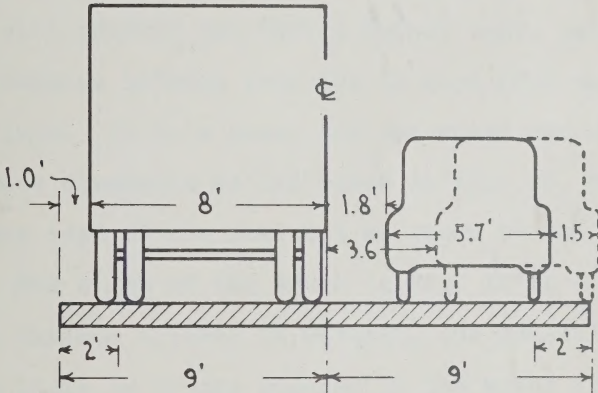


Fig. 13 Truck and Passenger Car Passing on an 18 Foot Pavement

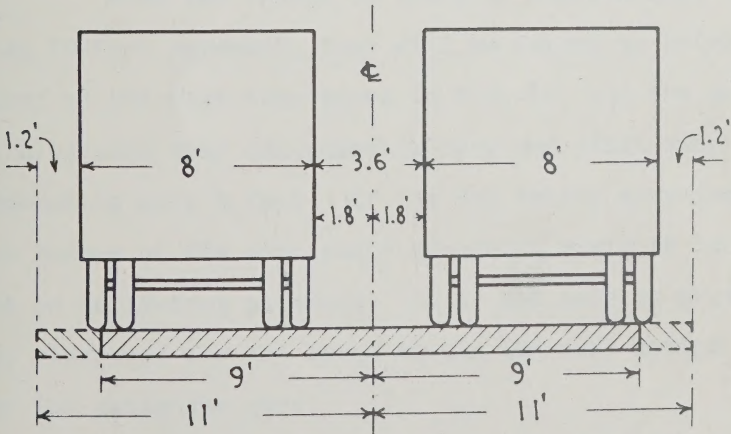


Fig. 14 Truck Passing Truck with 3.6 Foot Clearance 22 Foot Pavement Required

no nearer than about 2 feet from the outside edge of the pavement when passing other vehicles. Fig. 12 shows the position of passenger cars passing on an 18-foot pavement with their rear wheels 2 feet from the edge. The clearance between vehicles in this case is about 3 1/2 feet.

If, instead of two passenger cars, a truck and a passenger car must pass on an 18-foot pavement, the truck will require the entire 9-foot lane, leaving all the clearance between vehicles to come from the passenger car's lane. In this case, the passenger car must either sacrifice clearance as indicated in Fig. 13, or move to the very edge of the pavement as shown by the dashed outline. The width of the truck in Fig. 13 is 8 feet which is the maximum allowed in Ontario, and generally utilized to the limit by trucks engaged in the motor freight business.

When two trucks or buses of maximum size pass on an 18-foot pavement, they will be forced to drive closer to the edge than shown in Fig. 13, and the greatest clearance they can possibly have and still stay on the pavement is only 2 feet. If the two trucks approach within 6 inches of the edge their clearance would be but 1 foot on an 18-foot pavement. It is not safe to provide less clearance for the large trucks and fast moving buses than for passenger cars.

If the same clearances are provided for the vehicle of maximum width as is provided for the passenger

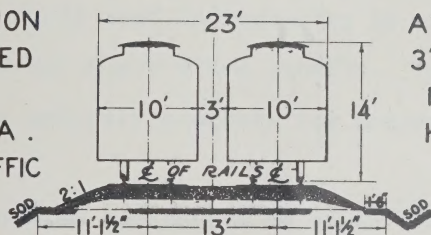
car on an 18-foot pavement, a 22-foot pavement would be required as shown in Fig. 14.

From the above it may be concluded that the motor truck and bus enjoy no more freedom of movement on a 22-foot pavement than does the passenger car on an 18-foot pavement, and that extensive use of 18-foot or even 20-foot roads by large vehicles impose a hazardous restriction upon the clearance which they may have between them in passing each other, and likewise impose a restriction on the passenger car in passing because the latter must provide the large vehicle with a disproportionate amount of clearance from the lane it is occupying. The greater occupancy of these 18 and 20-foot roads by these wider vehicles makes passing difficult and hazardous.

A paper* on "The Design of the Highway Cross-Section", by W. H. Simonson of the U.S. Bureau of Public Roads includes the diagram, Fig. 15, showing the normal spacing of railroad cars on fixed rails, and the position of two trucks with the same clearance on an 18-foot pavement, showing the total inadequacy of the 18-foot pavement for these vehicles and the necessity for a 22-foot pavement to provide a clearance comparable with that required on rails. Surely the mobile trucks on the highways require no less width than cars on fixed rails.

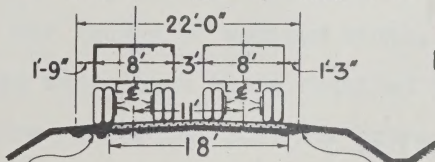
* Proc. 16th Annual Meeting Highway Research Board, Washington, D. C., Dec. 1937.

CROSS-SECTION
RECOMMENDED
BY THE
A. R. E. A.
CLASS 'A' TRAFFIC



ASSUMED MIN
3' CLEARANCE
FOR HEAVY
HIGH SPEED
TRAFFIC

9' LANES
INADEQUATE
FOR SAFETY



11' LANES
EASIER TO
MAINTAIN

"RUTS" CAUSED BY PASSING VEHICLES

(From "The Design of the Highway Cross-Section"
by W. H. Simonson, U. S. Bureau of Public Roads)

Fig. 15

The U. S. Bureau of Public Roads has recently made photographic studies of the passing of vehicles on the highways, (Public Roads, September 1937). They conclude

"Pavements of 18-foot width are too narrow for modern passenger cars alone or for modern mixed traffic. Pavements of 20-foot width are reasonably adequate for light-traffic roads used infrequently by wide trucks but are inadequate for heavy mixed traffic. Pavements of 22-foot width are entirely adequate for modern mixed traffic."

Hence the conclusion is drawn that if roads are built adequate for trucks of maximum width, they must be from 2 to 4 feet wider than those required for passenger cars which incurs additional cost for extra width of pavements, grading and bridges. If the extra width is not actually provided, the larger vehicles will demand and use it at the inconvenience and hazzard of the passenger car and other narrower vehicles.

The increase in the amount of mixed traffic was no doubt a major cause for the progressive widening of traffic lanes in Ontario during the period under review in this report, and for the change from 2-lane to multiple lane roads. Had there been no trucks or buses in the traffic stream, an increase in volume of passenger car traffic alone would not fully warrant the widening of traffic lanes and the construction of wider and firmer shoulders. With mixed traffic, however, the passages of truck with truck

and truck with passenger car multiply rapidly as traffic increases and the necessity for greater clearance becomes more and more important.

Additional Lanes

On highways where there is a high percentage of trucks, the faster passenger cars are constantly overtaking the slower trucks, and congested situations are common where these faster vehicles are held up because they cannot readily pass the impeding vehicle. The slower vehicle may occasionally be a slow passenger car, but more often it is a motor truck. The slow passenger car, however, can be passed readily because it does not occupy much of the width of the road and does not obstruct the view. With the motor truck a different situation exists. Its greater width and height obstructs the view, and its extra length requires much more time and much more open road in the adjacent lane for passing than is the case for a passenger car. When delays become excessive and congestion frequently occurs, additional lanes are required to relieve this situation. Motor trucks have a definite responsibility for this extra width since their excessive size and inherent slow operation will require additional lanes earlier than would be the case for passenger cars alone.

Because of the difference in speed of vehicles and particularly because of the slow speed of heavily

loaded trucks, extra lanes are required to prevent repeated delays and congestion resulting from the difficulty which the faster more mobile passenger cars have in readily passing the slower vehicles.

This condition is particularly acute on grades, where overloaded trucks often cannot travel more than 5 to 10 miles per hour. These locations are usually marked with restricting center lines so that it is a violation of the traffic laws to pass, even if no opposing traffic is present. For greater safety 3-lane roads are commonly restricted to 2-lanes at summits by painting a white line along the middle of the middle lane so that the center lane which is usually available for passing slower vehicles cannot be used. To relieve this situation, Ontario has in certain instances widened some of its 3-lane roads to 4-lanes at summits. Obviously the motor truck and the bus have a special responsibility for widening at hill tops and for the early adoption of multiple lane roads in general on commercial highways. These widenings are often very expensive because the deepest cut is at the top of the hill.

Additional Maintenance of Road Surfaces and Shoulders

There are certain items of maintenance expense which are a greater responsibility of the heavier vehicle than of the lighter ones. Excessive shoulder maintenance is caused by wide vehicles on pavements adequate for passenger cars, but inadequate for the wider vehicles; both through the wide and heavy vehicles running off the pavement and because they force other passing vehicles to use the shoulders.

Likewise a few passages of heavy wheel loads may cause failure in a surface that would have lasted for many years under the moderate loads of passenger cars and light trucks. This condition is most obvious when secondary roads are used as a detour for primary road traffic. The secondary road may have served its normal light traffic for many years, but wear out in a few weeks under heavy diverted traffic.

Shortened Life of Pavements

It was pointed out above that excessive maintenance and sometimes destruction results when roads adequate for light traffic are suddenly subjected to intensive use by heavy vehicles. The same destructive action is going on at a slower rate in high type roads under normal traffic having the usual proportion of trucks. Concrete pavements, for example, are subject to failure

due to fatigue; that is, they can withstand a certain load for a certain number of applications and then they break. The heavier vehicles are the ones which impose these critical loads. If only the lighter vehicles used the pavement, these critical loads would never be applied and the slab would last indefinitely so far as wheel loads are concerned. The heavier wheel loads, therefore, determine the life of the pavement. Their influence may not at first be apparent, but as time goes on and the number of applications of the critical load multiply, the pavement begins to crack and fail. A recent survey of pavement condition in Illinois showed that many of the pavements which were expected to last 20 or 25 years were already (in 10 to 15 years) in need of replacement. The roads in the worst condition were those on the heavily traveled truck routes.

Nuisance, Delays and Hazards to Other Traffic

Considerable delay and inconvenience is caused by trucks on 2-lane roads even when the traffic as a whole is relatively light. The effect of the slower trucks is to collect a long line of passenger cars waiting for opportunity to pass. This occurs especially where the alignment is crooked and the profile hilly. There may be long stretches of unoccupied road between these groups of vehicles, so that an observer standing by the road side would not get the impression that the road was congested,

but the actual effect on vehicles trailing behind the trucks on this road is the same as though general congestion was present. This congested condition often lasts several minutes and covers a number of miles until conditions favorable to passing are encountered.

A theoretical diagram has been prepared in Fig. 16 which illustrates how congested conditions arise, even when the total traffic is much less than that which would cause general congestion.

Referring to Fig. 16, the sloping lines graphically represent the progress of a group of vehicles in one lane of a 2-lane road. The slope of the lines represent the average speed of the vehicles; a slow moving vehicle has a steep slope, a fast moving vehicle has a flat slope. For example, T-1 represents a heavy truck which is leaving the starting point at 0. It is to travel to the right over distances marked at the bottom of the figure, and the time which it will take to traverse these distances is represented at the left of the vertical line marked "elapsed time". T-1 is assumed to have an average speed of 25 miles per hour; thus it travels a mile in about $2\frac{1}{3}$ minutes, and it will be noticed that the slope of the heavy line which represents the truck's progress is about $\frac{1}{3}$ the way between the 2 and 3 minute lines at the one mile post. Twenty-four seconds after this big truck goes by the starting point, a passenger car, P-1, enters, and 24 seconds later another passenger car, P-2, goes by

and so on for a total of 11 vehicles in addition to the big truck, each one passing the starting point at 24 second intervals, and one of them being a light truck, shown by dot-dash line and marked T-2. This spacing of vehicles corresponds to a traffic of 150 vehicles per hour in one direction or 300 vehicles per hour for both directions, which is less than occurs on some 2-lane roads during normal week day conditions. The proportion of 2 trucks to 10 passenger cars corresponds to 16.7 per cent of trucks with half light and half heavy trucks, which is also typical of average week day traffic on many 2-lane roads.

To simplify the study, each passenger car is assumed to travel at a uniform speed of 40 miles per hour when unimpeded, and the light truck, T-2, is assumed to travel at a speed of 35 miles per hour unimpeded.

The first truck, T-1, is the slowest vehicle in this group; therefore, it is never going to be impeded; in other words, it is the only vehicle of the 12 that is free to move as fast as it desires. It, therefore, is going to be the offender so far as impeding the other 11 vehicles is concerned.

Let us see how this impeding occurs. Beginning at the starting point, T-1 proceeds until it has run 2300 ft. when it will be noticed that the line representing P-1 meets the heavy line, representing T-1. At this point, car P-1, which started 24 seconds later than T-1, has

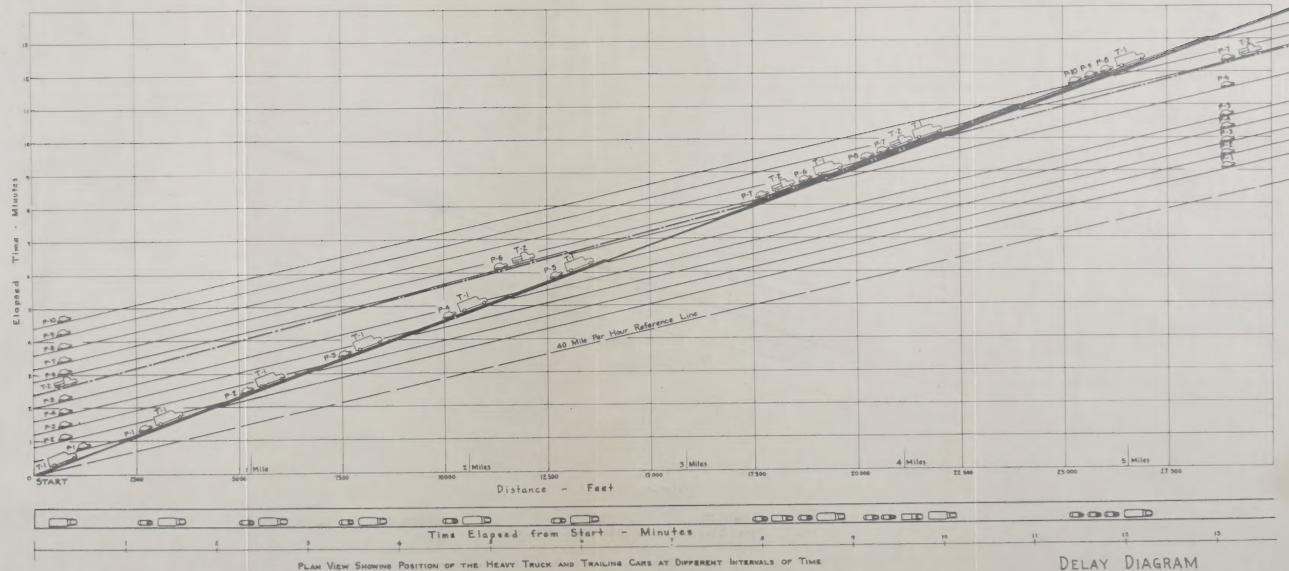
caught up with T-1 and begins to trail it. From observations which we have made, it has been found that under circumstances like this, an elapsed time of approximately one minute is a fair average time before P-1 can pass T-1 and start again at its normal speed of 40 miles per hour.

The diagram shows that P-1 began to trail T-1 at about one minute after T-1 passed the starting point. P-1 would not have passed T-1 then until about 2 minutes from the starting point, at which time T-1 would have reached 4500 ft. from the start. It will then be noticed that P-2 has caught up with T-1 and it begins to trail T-1 for a minute of time, and at about 3 minutes after the truck left the starting point, P-2 passes T-1 when it is about 1-1/4 miles from the starting point. A few seconds later P-3 overtakes and begins to trail T-1, so that as we proceed to the right in the diagram there is a passenger car trailing this truck nearly all the way from the starting point. In other words, Truck T-1 impedes one or more passenger cars practically all the time. it impedes P-1, P-2, P-3, P-4 and P-5 until P-5 passes it about 2-1/2 miles from the starting point. It then travels for about a mile (to the 3-1/2 mile point) where T-2 (the light truck) overtakes it. Previous to this, however, T-2, which started about 2 minutes and 10 seconds after the starting time has gone at such a rate that P-6 overtook it at about 2 miles from the start, followed

along behind it for 3000 ft. and then passed it, but soon after that P-6 caught up with T-1 and we find a group of vehicles at about 3-1/2 miles from the starting point with P-6, T-2 and P-7 all trailing the big truck T-1. And from there on to beyond the 6-mile post there are 3 vehicles trailing this big truck, but not always the same 3 as shown in the figure. The light truck is assumed to trail the heavy truck for one and one half minutes before it can pass, and every following passenger car is assumed to follow the heavy truck until one minute after all intervening trailing vehicles have passed the truck. These assumptions are all borne out by observations on actual road conditions.

The diagram can be worked out as far as desired. If it were extended to the right another heavy truck would immediately be encountered, and the same impeding of passenger cars would be repeated. The diagram shows that some passenger car and the light truck are trailing this heavy truck continuously. It likewise shows that each individual passenger car will have to trail behind some truck at least once every 6 miles or once every 10 minutes of traveling time. It shows that the only vehicle that has free unobstructed use of the highways is the slow moving heavy truck.

The presence of trucks on highways introduces a hazard to passenger cars that is so obvious that it hardly calls for special emphasis. A few of the commonest



DELAY DIAGRAM

hazards may be mentioned.

The larger vehicles on the highways often shut off the view of dangerous conditions in the road, such as railroad crossings, intersections, sharp curves, etc. These vehicles are so wide and high that following cars cannot see around them on 2-lane roads without pulling out into the lane of opposing traffic. After trailing a truck for some distance, a driver may think he has a good opportunity to pass, and after swinging out into the left-hand lane finds, often after it is too late to change his course, that there is a railroad crossing or red traffic light ahead the view of which the truck obstructed.

On long grades the heavy trucks slow down to such a slow pace that the following passenger car driver becomes exasperated at the delay and often attempts to pass against his better judgment and in violation of traffic rules. Accidents often result. The truck may suffer no damage from such an accident and may not be reported in any way, but yet it contributes to the cause of the accident.

Most drivers instinctively give trucks and buses a wide berth in passing, and run on to the shoulder. If the shoulder is soft or rutted they may be forced off the road and collide with the guard fence or trees.

Trailers are sometimes difficult to handle on down grades in slippery weather. Serious accidents have happened when the trailer has "jack-knifed" across the

road in the path of other traffic.

When the passenger car is stopped on the road it can pull off on to the shoulder and obstruct the lane not at all or only to a slight degree, but the truck driver does not dare drive out on to the shoulder because it is not firm enough to support his heavy wheel loads. He therefore stops on the highway and at night this produces a most critical hazard.

These are all very real dangers that exist on any highway that has truck travel and the highways that have the most truck travel are the King's Highways which carry the greater part of the total highway traffic.

Special Benefits to Heavier Vehicles from Road Improvements and Grade Reduction

When a pavement is improved, it is always given a smooth top surface which, it is definitely known, reduces cost of operation, principally fuel consumption. This is a much greater benefit to commercial vehicles than to passenger cars because their proportional saving is greater and they use many times more gallons of fuel during a year, and therefore save more money annually per truck than per passenger car. It has been estimated, as between a fairly rough bituminous pavement and a new smooth surfaced pavement, that there is a saving of 1/2¢ per mile for passenger cars.

Suppose, for example, that the saving is only

1¢ per mile for a truck, (experimental evidence indicates that this is conservative) then if the truck traveled 30,000 miles over improved pavements this year whereas it traveled 30,000 miles over worn, though not failed, pavements last year, it would save \$300 a year in operating costs. There will also be savings in tire and mechanical wear. The total saving may amount to from one to two cents a mile; then improved surfaces will readily effect an economy of \$300 to \$600 a year in operating expenses for the heavier vehicles.

Likewise the grade requirements of passenger cars and trucks vary greatly because of the difference in reserve power of these vehicles. Passenger cars have no difficulty in climbing grades up to 9 per cent, but only light trucks can maintain normal speed on grades over 4 per cent, and many of the heavier trucks are obliged to climb along grades of 3 per cent and greater at a snail's pace.

Where the grades are not reduced to meet truck requirements, passenger cars are obliged to trail along behind the slow-moving trucks, which situation very materially increases the cost of operation of these passenger cars, not only because of the additional expense for fuel but also because of the loss of time.

The maximum standard grade for primary roads in Ontario is 4%, formerly it was 5%. Grades of this magnitude offer no obstacles to passenger car traffic and have little affect upon their operating cost, in fact grades of

6% would be satisfactory for passenger cars alone. When grade reductions are made below that required for passenger cars the resulting benefits are almost wholly to trucks. This has been borne out by a study of "Motor Vehicle Requirements on Highway Grades" by Prof. R. A. Moyer, published in Proceedings of Fourteenth Annual Meeting of the Highway Research Board, U.S.A. He reaches the following conclusions, among others:

"The savings in fuel costs, resulting from grade reduction were greater for trucks than for passenger cars, although the total tonnage was the same.

"For grades lower than 9 per cent, the time saving obtained from grade reduction is negligible for passenger cars but is an important factor in truck operation on grades steeper than 3 per cent."

A similar investigation has been made by Shaw and Fontaine at the University of North Carolina and published in Bulletin No. 7 of North Carolina State College Experiment Station, January, 1935. In this report the following table is presented which shows the extra cost of gasoline on grades up to 6 per cent for different classes of vehicles and indicates the possible savings due to grade reduction.

ESTIMATED EXTRA COST FOR GASOLINE OVER THAT
ON THE LEVEL, IN CENTS PER VEHICLE-MILE

CLASS OF VEHICLE	PER CENT OF GRADE						
	0	2.5	3	3.5	4	5	6
Passenger Cars	0	0	0	0	0	0	0
1 1/2-ton and smaller trucks	0	0	0	0	0	0.4	0.6
2- and 2 1/2-ton trucks.....	0	0	0	0	1	1.9	2.4
3 1/2-ton trucks.....	0	0.9	1.2	2.3	2.7	3.5	5.9

It will be noticed that grade reduction below 6 per cent is of no advantage to passenger cars but of considerable benefit to trucks, particularly the larger trucks. The authors commented as follows:

"Thus the conclusion is reached that the operation of passenger cars justifies very little, if any, expenditure for reducing grades up to 6 per cent, unless dense traffic causes low speeds and stops. Grade reduction, however, may be necessary in order to secure greater safety of operation.

"That grade reductions of grades up to 6 per cent must be justified mainly by the medium- and heavy-truck traffic."

Hence it appears that grade reduction below 6 per cent not only involves unnecessary construction cost for passenger car traffic but also reduces operating costs for trucks without effecting similar savings for the passenger cars.

Relative Road Occupancy of Trucks and Passenger Cars

A measure of the relative use made of the highway by the motor truck and by the passenger car may be had by developing a factor that will take into account the relative size and speed of the two classes of vehicles. Such a factor may be called the "road-occupancy" of the vehicle. It is equal to its width times its length times its height times the time it takes for it to travel a distance equal to its length. The product of the overall dimensions of the vehicle gives the volume which the vehicle occupies on the highway. The time which is required for

the vehicle to travel its length measures the time required for this volume to displace itself on the highway.

Figure 17 shows the relative road-occupancy at different speeds for a passenger car, for an average truck and for a combination of vehicles. The dimensions used for these vehicles are noted on the diagram, together with the general expression for road-occupancy.

The passenger car at 40 miles per hour has a road-occupancy of about 100. The average truck running at 27.5 miles per hour has a road-occupancy of 1240, which is 12 times that for a passenger car. The maximum truck and trailer combination permitted in Ontario at 22.5 miles per hour has a road-occupancy of 7330, or 73 times that of the passenger car at its usual speed of 40 miles per hour. These speeds have been taken as typical. If all vehicles are assumed to travel at the same speed, say 40 miles per hour (which is an unreasonable assumption), even then the average truck would make 8½ times as much use of the road as the passenger car, and the truck and trailer combination would make 41 times as much use as the passenger car.

Figure 17 takes into account the size and speed of vehicles but it does not take into account the relative use of the highways as reflected by the different annual mileages of the different types of vehicles. Fig. 18 has been prepared which is similar to Fig. 17, but introduces a "mileage factor" which takes into account the greater

Road Occupancy = Width x Height x Length x Time to travel Length

$$\text{For Passenger Car} \quad 5.7 \times 5.7 \times 13.5 \times \frac{13.5 \times 3600}{5280 M} = \frac{4.030}{M}$$

$$\text{For Average Truck} \quad 8.0 \times 10.0 \times 25.0 \times \frac{25 \times 3600}{5280 M} = \frac{34.090}{M}$$

$$\text{For Maximum Combination permitted in Ontario} \quad 8.0 \times 12.0 \times 50.0 \times \frac{50 \times 3600}{5280 M} = \frac{163.640}{M}$$

Where M = Miles per hour

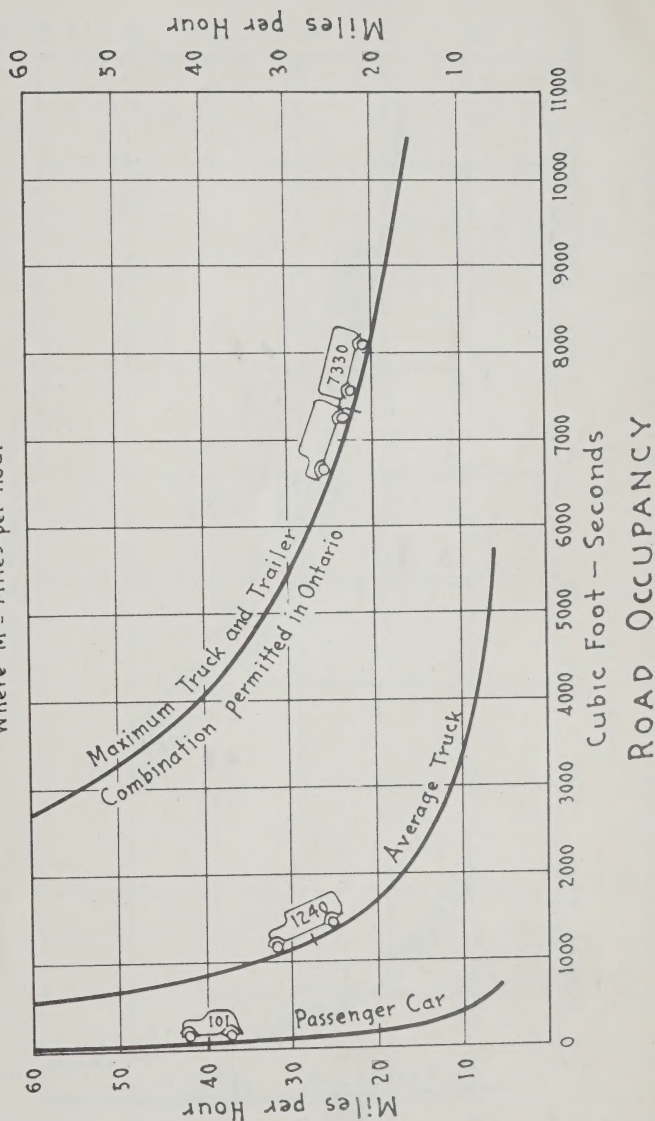


Fig. 17

Road Occupancy with Mileage Factor
 equals Width x Height x Length x Time to travel Length x Mileage Factor

For Passenger Car	$5.7 \times 5.7 \times 13.5 \times \frac{13.5 \times 3600}{5280 M} \times 1.00 = \frac{4030}{M}$	Annual Mileage = 6,300, Factor = 1.00
For Average Truck	$8.0 \times 10.0 \times 25.0 \times \frac{25 \times 3600}{5280 M} \times 2.54 = \frac{86,590}{M}$	" " = 16,000, " = 2.54
For Maximum Combination permitted in Ontario	$8.0 \times 12.0 \times 50.0 \times \frac{50 \times 3600}{5280 M} \times 4.12 = \frac{674,180}{M}$	" " = 26,000, " = 4.12

M = Speed in Miles per Hour

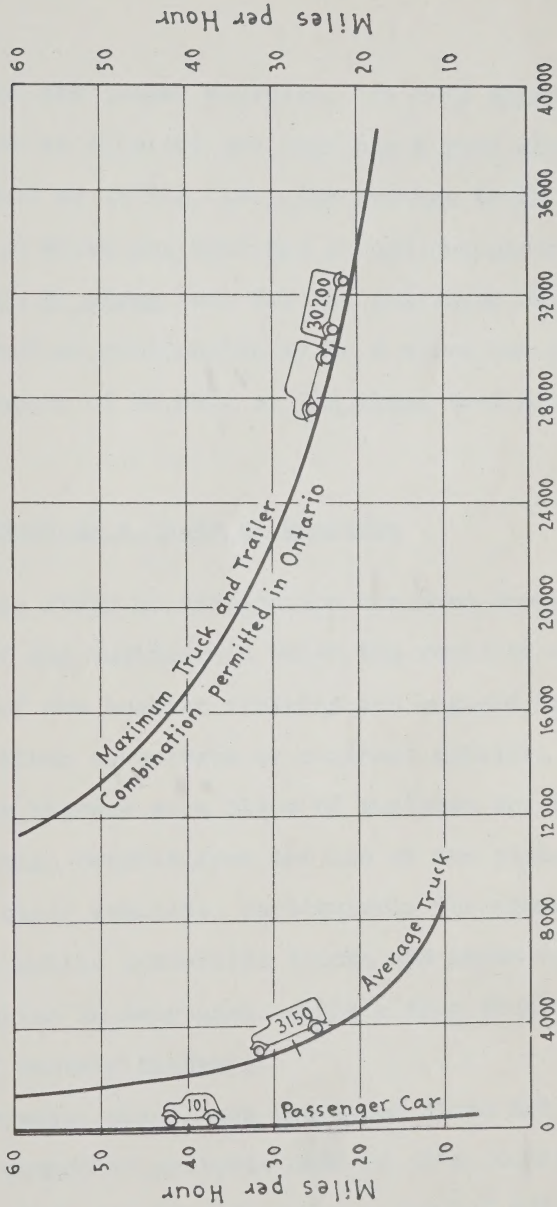


Fig. 18

ROAD OCCUPANCY WITH MILEAGE FACTOR

Cubic Foot - Seconds

annual mileage of the larger vehicles. In this diagram the passenger car at 40 miles per hour has a road occupancy of about 100 as in Fig. 17. The average truck traveling at 27.5 miles per hour has a road occupancy of 3150, which is 31 times that for the passenger car. The truck and trailer combination at 22.5 miles per hour has a road occupancy of 30,200, or 302 times that of the passenger car.

Use of the Highways as a Place of Business

In this study no distinction has been drawn as to the nature of the business in which the vehicles are engaged. Many of the heavier vehicles are engaged in highway transport either as private or contract carrier. These vehicles use the highway as a place of business and therefore derive special benefit from the use of the highways not enjoyed by other vehicles, particularly the passenger car group. The public commercial trucks and buses operate under permits which in many cases entitle them to a monopolistic use of certain highways.

The special privileges mentioned above are not charged in the method of analysis used in this report; they represent ample justification for a special privilege tax over and above that required to cover the cost of highway facilities and use made of them.

Summary

This study has developed the following outstanding facts and conclusions.

The motor vehicle influence began in the period 1900 to 1910. It did not have any considerable effect on highway costs until about 1918. In this study, none of the expenditures prior to 1919 have been charged to the motor vehicle user; their value is treated as full compensation for the social-necessity use of highways.

It was at first intended to charge the total highway costs for the period between 1918 and 1937 (18 years) to the motor vehicle user; the great increase in highway costs was on account of the motor vehicle. When the costs and revenues for this period were compared, however, it was found that the motor vehicle during those 18 years had paid only about one-half the total annual cost, and that consequently there was an accumulated highway debt of \$326,000,000. This debt was placed arbitrarily upon the public because, if added to the proposed charges to be made to the motor vehicle users, it would impose such excessive charges as to be impracticable. As an expediency, therefore, this debt of \$326,000,000 was deliberately given to the general public to amortize and it was suggested that it be amortized over a period of 50 years, at the rate of about \$14,000,000 per year.

This having been done, the annual cost to be

paid for in the future entirely by motor vehicle users amounted to about \$51,000,000. This annual cost was allocated to the different classes of vehicles by the application of the so-called "increment" method to cover facilities required modified by a ton-mile charge to cover use made of the highways. This resulted in raising the charge for the average passenger car from \$27 to \$43 and for the heaviest class of trucks (10 to 15 tons gross load) from \$431 to \$4253.

APPENDIX A

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VII. DESIGN OF ASPHALT PAVEMENTS

129. FLEXIBILITY AND RIGIDITY.—Bituminous pavements are classified generally as "flexible surfaces". Actually it is possible to build asphaltic concrete and similar types so as to behave like rigid pavements, but this is not desirable because a slight yielding to meet the changing conditions of temperature and traffic is a distinct advantage in providing for greater durability and lower maintenance.

There are two approaches to the rational design of pavements. In the rigid type it has been assumed that by constructing a slab having high tensile strength, all weak areas in the subgrade would be bridged and the load thus transferred to stronger adjacent support. Cracking occurs when this support is not provided, and in a sense it is like designing a bridge without information as to location of the piers and abutments. In the flexible type it is assumed that the pavement will be always in continuous intimate contact with the subgrade and that the load will be transmitted to it in a substantially uniform manner without the concentration which occurs under bridging action.

There has been some misunderstanding in regard to the manner in which loads are transmitted through flexible pavements to the subgrade. When a load is applied to such surfaces through a bearing area, there are two fundamental resistances developed; one, perimeter-shear which is a function of the length of perimeter of the bearing area, and second, internal compressive resistance which is a function of the area involved. As the load is applied and for surface deflections of minor char-

[77]

acter (.00 to .05 inches), resistance to perimeter shear develops rapidly. This rate of increase in shear resistance with small deflections may be so great that there will be a negative moment under the center of the bearing area. As loading increases, resistance due to compression becomes a factor and further deflection is opposed by the combined effect of both perimeter-shear and the pressure resistance developed in the body of the pavement. In turn, lesser intensity loads are distributed to the base and subgrade; lesser because applied over a greater area, and because of an irregular area of loading as contrasted with the area of tire contact.

It is evident that the ability to transmit loads most efficiently (through high shear values) will

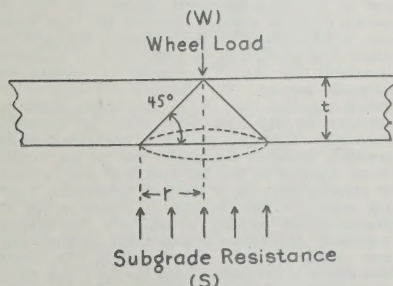


Fig. 21 Distribution of Surface Loads Through Flexible Pavements

[78]

thus depend:—upon the density of surface and base, upon a high degree of internal friction between particles or a combination of the two. The duration of load application is of great importance, as the shorter the period the more nearly does any surface behave like a completely elastic substance. This means that dynamic resistance usually outweighs any actual impact forces, and that a design which contemplates static load conditions will be entirely adequate for these same loads in motion. This has great bearing in highway and airport design where loads are fleeting in character.

From these premises it is thus possible to proceed to a mathematical determination of thickness requirements.

130. DISTRIBUTION OF LOADS.—A static load applied to the surface of a stable, flexible pavement is distributed downward in a conoidal fashion. The boundary of this pressure cone is a surface which in cross-section is defined by the limiting angle of pressure distribution. This angle varies with the depth and with the applied load, but in regions of low stress (at bottom of pavement) approaches a slope of 2 to 1 (horizontal to vertical). For all practical purposes it is sufficient to assume this angle as 45°, and the area over which pressure is applied as a circle having a radius equal to the pavement depth. (See Fig. 21.) Pressure distribution over the base or subgrade while not absolutely uniform, may be so assumed for purposes of calculation and an adequate margin of safety to care for this variation will be provided by increasing the subgrade support 50% above that theoretically required.

It is evident therefore that the pavement thickness must be sufficient to provide distribution of load over a large enough area of subgrade so that

[79]

its total resistance shall not be exceeded. To have equilibrium the following equation is obvious.

$$\begin{aligned} W &= \pi r^2 S \\ \text{In the } 45^\circ \text{ triangle } r &= t \\ \therefore W &= \pi t^2 S \\ \text{and } t &= .564 \sqrt{\frac{W}{S}} \end{aligned}$$

Where

t = thickness of pavement in inches.
 W = wheel load in pounds.
 r = radius of circle of load distribution (inches).
 πr^2 = area of circle of load distribution.
 S = subgrade resistance in pounds per sq. in.

This equation assumes application of load at a point, whereas actually it is applied over an area, this area depending upon the number and kind of tires, and their contact area when under load. The effect is to develop a higher resistance to shear and to distribute the load over a greater area of subgrade. This increased shear value and greater distribution of load exists up to a certain critical area, which is approximately 100 square inches. However, as this is about the maximum area of the tire contact under the heaviest truck loads, it is to be noted that the usual highway traffic is of a kind most favorable for development of the maximum bearing value in soils. (See Fig. 22.)

The minimum required thickness is thus reduced as shown in the following equation:

$$\begin{aligned} W &= \pi r^2 S \\ \text{In the large } 45^\circ \text{ triangle } r &= t + e \\ \therefore W &= \pi (t + e)^2 S \\ \text{or } t &= .564 \sqrt{\frac{W}{S}} - e \end{aligned}$$

where e = radius of tire area contact

Fig. 23 shows the required thickness of pavement with relation to subgrade support.

[80]

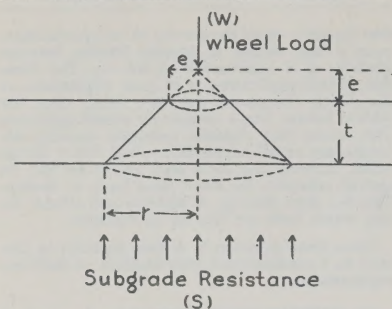


Fig.22 Effect of tire contact on Load Distribution

Subgrade resistance varies according to changes in moisture, and pavement thickness should be designed therefore for the most adverse condition, which is usually during early spring. Any soil at its optimum moisture content has a resistance sufficient to carry the highway load, and as reduced support comes usually from too much moisture, the first item in subgrade design is to provide adequate drainage. No matter what it costs to drain a roadbed properly, it is the cheapest method for insuring maximum subgrade support. Corrugated iron pipe or clay tile for culverts and seepage drains are both inexpensive, efficient and highly durable, while proper side ditches and an elevated roadbed should be obtained wherever possible, so as to lower the ground water level.

[81]

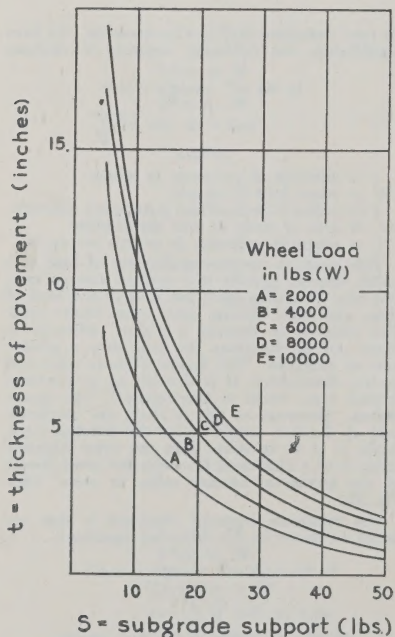


Fig.23 Thickness of Pavement with Relation to Subgrade Support

[82]

131. RELATION OF SUBGRADE TO DESIGN.—The design of flexible pavements thus includes two elements—the pavement itself and the subgrade upon which it rests. Economy in design can be obtained either by varying the pavement thickness according to the natural subgrade support or by increasing the subgrade resistance through admixtures of low cost aggregates, chemicals, bituminous products* or combination thereof. Selected cheap local materials may be used to construct a course between subgrade and base. Such materials as sand-clay, disintegrated granite, tuff and pit-run gravel are employed. As a practical matter it is best practice to bring the subgrade to a uniform condition over the entire road length, so that pavement thickness will be uniform throughout and construction procedure simplified. The admixture of as little as 2 inches of stone screenings or sand to a subgrade will often change its support value from 10 lbs. to 20 lbs. or more per sq. in. thereby markedly reducing the required pavement thickness. Such possibilities are all too frequently overlooked, largely because evaluation of subgrade often is made by guess instead of by measurement. For example, from Fig. 23 it will be noted that for a 25 lb. subgrade, and a 10,000 lb. wheel load, a pavement thickness of a little over 5 inches is required, while for a 10 lb. subgrade and a 50 lb. subgrade and the same load, 12 inches and 2 inches respectively are required.

For various types of asphalt pavements, there is usually a given thickness which is most economical to construct, by reason of either the aggregate particle size available from commercial production, or the limitations of equipment manipulation. Thus in penetration macadam, $2\frac{1}{2}$ inches to 3 inches depth is best because stone can be prepared most effi-

* See Public Roads, May, 1936.

[83]

DESIGN OF ASPHALT PAVEMENTS

ciently in these sizes and asphalt can be forced into the voids in a satisfactory manner. Asphaltic concrete can be thoroughly consolidated in layers up to 4 inches depth for coarse mixes and 3 and 2 respectively for finer mixtures. Road-mix surfaces can be mixed thoroughly and spread and rolled efficiently in depths up to 3 inches, while surface treatments can be handled in amounts up to one inch depth.

An asphalt pavement is thus designed from the surface downward, first selecting the wearing course, next the base, and finally, bringing the subgrade up to the required support. The base thickness should be determined by balancing the cost of its increased depth against the cost of raising subgrade support. Usually the base thickness is determined by the minimum thickness to which it is practicable to build it, as it is almost invariably true that it is cheaper to increase the subgrade support. For example, $4\frac{1}{2}$ inch water-bound macadam base is an economical depth to construct in one layer, and would be generally employed. It is deep enough to use commercially available stone to advantage, and to be closely keyed together so that no weak area can develop. In combination with a $2\frac{1}{2}$ inch penetration wearing course, it then becomes a simple matter to determine the amount of subgrade stabilization required. As a factor of safety, this subgrade support should be made approximately 50% above that shown in the table. Thus for the 7 inch pavement depth, under a 10,000 lb. wheel load, a subgrade support of 20 lbs. is indicated. It should be brought up to 30 lbs.

The design of cross section for flexible pavements is also different from rigid pavements and, while a thickened edge is desirable for certain types of cold-laid mixtures and surface treatments,

[84]

DESIGN OF ASPHALT PAVEMENTS

this is to prevent the entry of water between base and wearing course, rather than to give added support. The pavement thickness should be uniform and, if there is more danger of loss of subgrade support at the outside of a pavement, the remedy is to increase it at such points, rather than to thicken the pavement. It is necessary, however, that the base be of sufficient width so that a load applied at the edge of the surface course may be transmitted to the subgrade. This increased base width on each side should be at least equal to its depth, and as a matter of practice seldom should be less than 12 inches. The shoulder material should be brought over this widened base, so that traffic will be confined to the surface only.

132. BASES AND SURFACE COURSES.—The pavement proper is usually constructed in two layers, the lower layer called the base and the upper layer the surface course. This is done largely for the purpose of economy as, while the surface of a road must resist abrasion and the entry of water, the lower portion only needs to supply stability under distribution of traffic load. The relative thickness of base and surface course should be determined according to available aggregate, climate and traffic conditions. As a rule the principal differences are the use in the base of larger size aggregate, a lesser volume of asphalt or both. For example, sand-asphalt uses the same aggregate but a leaner mixture for the base course, while asphaltic concrete bases contain both larger aggregate and less asphalt.

Sometimes the base course is composed entirely of non-bituminous materials, such as waterbound macadam, portland cement concrete or sand-clay mixtures. (See Chapter X.) Macadam bases are employed under all types of surface but particularly penetration macadam and cold-laid mixtures.

[85]

Sand-clay, limerock and similar bases are usually covered with heavy surface treatments.

133. TYPICAL CROSS SECTIONS.—A base thickness greater than 6 inches is rarely required, as it is usually possible to increase the subgrade resistance even under most adverse conditions to at least 25 lbs., for which value a total pavement thickness of 5 inches is sufficient. The surface course thickness is controlled largely by construction requirements, which include size of aggregate employed, and character of spreading and finishing operations. Mixed surface courses are usually $1\frac{1}{2}$ to 2 inches thick when using sand and 2 to $2\frac{1}{2}$ inches when using coarser aggregates, while for penetration macadam $2\frac{1}{2}$ to 3 inches is required. As a general rule the base should be thicker than the surface course as more complete balance is thereby obtained. Some typical cross sections for different types, as shown in Fig. 24, will indicate these relationships.

134. RELATION OF TRAFFIC TO TYPE AND DESIGN.—The several sections in Fig. 24 are not interchangeable for all conditions of traffic and climate, and there is thus brought in the selection of type for a given situation as the final item in design. In such selection, probable traffic changes within the expected pavement life should be appraised, after careful traffic surveys, and plans provided for additional pavement thickness as required. This latter procedure is termed stage construction, and often makes for great economy because of the very large difference in the traffic load upon the several classes of highways. The 10,000 lb. wheel loads are confined largely to city streets and trunk lines, and pavements thereon should be designed accordingly. Secondary and third class roads seldom have wheel loads exceed-

[86]



1" hot surface treatment on
8" limerock base



2" macadam road-mix top on
6" gravel base



$2\frac{1}{2}$ " penetration macadam top
 $4\frac{1}{2}$ " waterbound macadam base



2" asphaltic concrete top on
3" asphaltic concrete base



$1\frac{1}{2}$ " sheet asphalt top
 $1\frac{1}{2}$ " asphalt binder course
6" p.c. concrete base



$1\frac{1}{2}$ " sheet asphalt top
 $3\frac{1}{2}$ " asphaltic concrete base

Fig. 24 Typical Sections

[87]

ing 4,000 lbs. (a five ton truck) and, whereas for a 25 lb. subgrade a pavement thickness of 6 inches or more is required for the heaviest loading, one-half that amount is sufficient on the secondary roads.

Thus surface treatments and road-mixes would be used for the lighter traffic situations, with asphaltic concrete, sheet asphalt and penetration macadam for heavy traffic. The selection of type within each group is largely a matter of aggregate availability rather than difference in durability. In the south where sand-clay and limerock are available, very strong bases may be constructed cheaply, and the hot asphalt surface treatment is all that is required to take abrasion and distribute the traffic load. Where excellent trap rock abounds, penetration macadam is the logical choice and similarly for coastal areas sand mixes would be most economical, with stone or gravel types in more inland locations.

In some cases purely local aggregates are not strong enough in themselves for a given type but are the only ones available. It has been learned that often a very small amount of imported aggregate will correct the deficiency and permit the use of local aggregates in mixtures, after first determining proportions as a result of a series of tests with the stability machine. (See 86.) Often soft stone or gravel will be substantially toughened after coating with asphalt and make satisfactory bases, while in an untreated condition they would not be suitable. Such potentialities may be developed through proper laboratory studies, which are all too often overlooked.

135. SURFACE TEXTURE.—In recent years much attention has been given to the non-skid character of pavement surfaces, with a marked tendency toward the construction of quite open

[88]

coarse textures. This trend was emphasized until many wearing courses were being laid which were extremely porous. Recent exhaustive studies at Iowa State College have conclusively shown that the sand-paper finish usually present on sheet asphalt or asphaltic concrete has the highest coefficient of friction of all pavements. The action of balloon tires now produces a tearing action in place of the kneading action of the old hard tires, and there is now little tendency to close a pavement surface for which allowance need be made. In view of the fact that a dense surface is the most waterproof and durable, all open or porous texture surface courses should be finished with a thin but rich seal coat covered with fine aggregate. One-tenth to one-quarter gallon asphalt per square yard covered with a slight surplus of sand cover will usually be sufficient. Hot-mix surfaces and penetration macadam are exceptions as they carry such a heavy asphalt content as to be completely waterproof without sand asphalt seal coats. (See Chapter VIII.)

One current practice in finishing sheet asphalt is definitely harmful; that of applying a dust cover to the finished surface. This cover serves no useful purpose, fills the voids between the sand grains of the surface and often covers defective construction procedure. Its requirement in specifications is a carry-over from the past when plant control was less efficient and, under no circumstances, should it be now permitted.

136. **EDGE PROTECTION.**—The practice of building portland cement concrete edging for rural asphalt pavements is not only a wasteful extravagance but also is detrimental to the pavement itself. This does not apply to urban and suburban curb and gutter construction which is an entirely different matter — where the curb is required for

[89]

DESIGN OF ASPHALT PAVEMENTS

drainage control and sidewalk support. Except for curb and gutter construction portland cement concrete edging should be omitted. It adds nothing to the strength of the pavement and is certain to separate from it, thus permitting entry of surface water as well as retaining ground water which would otherwise drain off at the sides. Its cost is so high that either the asphalt pavement proper may be widened several feet or the entire shoulders may be of low cost asphalt construction such as surface treatment, road-mix or plant-mix for less than the cost of the edging.

APPENDIX B

Do the Accepted Laws of Soil Mechanics Support the
Square Root Relation in the Design of Flexible Pavements?

by C. B. Breed

assisted by Glennon Gilboy and D. W. Taylor*

This analysis shows that when the intensity of pressure on a pavement is the same but the wheel load is increased the thickness of all types of flexible pavements must be increased as the square root of the wheel load if the intensity of pressure is to remain the same on the subgrade; and that if, as the wheel load increases, the intensity of pressure increases on the pavement the thickness of the pavement must be increased at a rate greater than in proportion to the square root of the wheel load if the intensity of pressure on the subgrade is to remain the same.

One of the most important functions of a pavement is to distribute wheel loads to the subgrade in such a manner that the load-carrying capacity, or bearing capacity, of the subgrade is not exceeded. If the bearing capacity of a given subgrade is 1 ton per square foot, it is obvious that the application of a wheel of 2 tons

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per square foot will produce failure. Such overloading is responsible for the badly rutted condition of unimproved roads when excessive loads are applied, or when the bearing capacity has been temporarily reduced by frost or excess moisture. It is equally obvious that a pavement constructed on such a subgrade must be of sufficient thickness to allow a load applied on the surface to spread enough so that the pressure on the subgrade will be well within the maximum allowable. Hence a study of the manner in which applied loads are transmitted through pavements is of great value in analyzing the effects of different vehicles.

The classical theory of load transmission was developed by Boussinesq in 1885. According to this theory, if a load P is applied at a point on the surface of a supporting material, it will produce stresses within the material according to the following equation:

$$q = \frac{3}{2\pi} \frac{P}{z^2} \cos^5 \theta$$

wherein q is the vertical stress at any point within the material whose position is determined by its depth, z , and the angle, θ , between the vertical and a line connecting the given point with the point of load application. (See Fig. 1.)

The ideal material which Boussinesq had in mind when developing this theory would be best represented by a large block of steel. However, its application

to other solids and to soils has given results which check with actual measurements closely enough for practical engineering purposes.

Application of this equation is extremely simple. Assume a load of 1000 lbs. on the surface of a pavement 8" thick. (Fig. 2.) The stress on the subgrade directly under the load would be $\frac{3}{2\pi} \times \frac{1000}{8^2} \times 1 = 7.46$ lbs. per sq. in. The stress 6" out from this point would be $\frac{3}{2\pi} \times \frac{1000}{8^2} \times \left(\frac{4}{5}\right)^5 = 2.44$ lbs. per sq. in. Proceeding in this fashion to other points, a complete picture of the stress on the subgrade can be obtained, as shown in the sketch. Now suppose that the load is increased to 4000 lbs. A glance at the equation shows that the stress at every point on the subgrade would be quadrupled, the maximum becoming 29.84 lbs. per square inch. Or, in general, the intensity of stress increases directly with load.

Next assume that the character of the subgrade is such that the stresses produced by the thousand-pound load are about as much as the subgrade can stand. The quadrupled stresses under the 4000-lb. load would, therefore, be expected to produce failure. The next question is: how much thicker should the pavement be to support the 4000-lb. load? The equation shows that if P is quadrupled z must be doubled to obtain the same stresses. The pavement, therefore, should be 16 inches thick. Or, in general, the required thickness increases with the

square root of the load.

The foregoing analysis has been based on a load applied at a mathematical point, which is, of course, a practical impossibility. A wheel load applied to a pavement is distributed over an area dependent on the characteristics of the tire. The next step is to investigate the effect of this distribution upon subgrade stresses. In particular, if tires were so designed and inflated that the 1000-lb. and the 4000-lb. loads of the previous example produced equal pressures per unit of area on the pavement, would not this equalization of surface pressure automatically produce equal stresses in the subgrade?

The answer to this question is not as easy to obtain as was the case with the point loads. However, a useful approximate solution can be developed by a method widely employed in the design of building foundations. This method consists of assuming the load to spread at a certain angle outward from the area of application, thus obtaining an average load intensity on any lower level. An illustration will make the method clearer than a more detailed explanation. (Fig. 3.)

Consider that the 1000-lb. load of the previous example is spread over a circular area such that the average pressure is 35 lbs. per square inch. The area would then have a radius of about 3.02 inches. Assume a spread coefficient of $1/2$. Then at the bottom of an 8" pavement the radius would be 4" greater, or a total of 7.02 inches.

The area of a circle of this radius is 154.8 sq. in. Dividing the load, 1000 lbs., by this area gives an average intensity on the subgrade of 6.46 lbs. per sq. in., as indicated in the sketch.

Now assume that this stress is about all the subgrade can stand, and work backward to find the thickness of pavement required for the 4000-lb. load. This load, at a pressure of 35 lbs. per sq. in., would be spread over an area of radius 6.04 inches. The radius of the subgrade area required to maintain an intensity of 6.46 lbs. per sq. inch would be 14.04 inches. Subtracting the two, the increment of radius produced by the spread would have to be 8 inches, corresponding to a pavement thickness of 16". Here again, quadrupling the total load requires doubling the thickness of pavement.

This result can be generalized by developing a simple formula. Let the average surface pressure be spread over a circle of radius r and let the average subgrade pressure be q , over an area of radius $r + kd$, where d is the pavement thickness and k is the coefficient of spread. Since the total load is the same, the following relation must hold:

$$p \pi r^2 = q \pi (r + kd)^2$$

This can readily be transformed into

$$\sqrt{\frac{p}{q}} - 1 = \frac{kd}{r}$$

In this form, the equation is most instructive.

If the intensity of surface pressure, p , is to be kept

constant, an increase of total load merely means an increase in r ; quadrupling the load doubles r . Furthermore, if the subgrade pressure, q , is to be held constant, the whole left-hand side of the equation is constant. Hence an increase in r must be exactly matched by an increase in d , irrespective of any assumption made as to the value of k . Thus the conclusion is again reached that, for equal surface and subgrade pressures, the thickness of pavement increases with the square root of the load.

It might be argued that the simple spread assumption just outlined gives results so far from the real distribution that no valid conclusions can be drawn. In fact, however, solutions more nearly correct mathematically lead to the same general relation. For example, S. D. Carothers in "Elastic Equivalence of Statically Equipollent Loads", Proceedings of the International Mathematical Congress in Toronto (1924), Vol. II, p. 518, gives for the maximum stress intensity beneath a circular loaded area the expression:

$$\hat{z}z = - \frac{P}{2\pi} (\omega - z \frac{d\omega}{dz})$$

where $\hat{z}z$ is the vertical pressure (which we have designated as q) at a depth z due to the surface pressure P (which we call p) and ω is the solid angle subtended by the loaded circle at the point and is equal to

$$\omega = 2\pi \left\{ 1 - \frac{z}{\sqrt{z^2 + r^2}} \right\}, \text{ where } r \text{ is the radius of the}$$

loaded circle, which, differentiated, becomes

$$\frac{d\omega}{dz} = - \frac{2\pi}{\sqrt{z^2 + r^2}} \left\{ 1 - \frac{z^2}{z^2 + r^2} \right\}.$$

Calling compression positive and substituting the above values in the original formula, the expression becomes:

$$q = p \left[1 - \left(\frac{1}{1 + \left(\frac{r}{z} \right)^2} \right)^{\frac{3}{2}} \right]$$

the notation being as shown in Fig. 5.

Since the relation between r and z is a simple ratio, it is evident that for equal surface and subgrade pressures - i.e., p and q constants - any change in r produced by a change in total load must be matched by an equal change in z ; and, since r increases with the square root of the load, z , or the depth of pavement, must also increase with the square root of the load.

A few words on the subject of bearing capacity are now in order. It has been assumed in this discussion that the sub-grade could withstand a certain amount of stress, and that an excess beyond this amount would produce failure, irrespective of the area over which the stress might be applied. This is true of solids, and it is also true of subgrades deriving the major portion of their strength from cohesion. It is not true of a cohesionless soil, such as gravel. The criterion is

whether the soil is of approximately constant strength within the zone of stress, or whether it becomes stronger with depth. In cohesive soil the former is the case; in cohesionless, the latter. Thus, if a load of 3 tons on an area 1 foot square applied to a bed of gravel produces failure, an intensity of 9 tons per square foot, or a total of 81 tons, would be required to produce failure of an area 3 feet square. The reason is that under the larger area the stresses go correspondingly deeper, where the material is stronger.

However, there are two reasons why this increase of strength of cohesionless soil does not vitiate the conclusions previously reached. First, the weight of a pavement produces considerable surface strength in a gravel subgrade, and the stresses due to wheel loads become negligible beyond a relatively shallow depth; hence the increase in strength within the stressed zone is not as important as might at first be assumed. Second, pavements laid on good sand or gravel subgrades seldom give trouble; the poorer subgrades, which are by far the more numerous, are the ones requiring careful design; and these are the types of material to which the preceding analysis most closely applied.

Thus it appears that the best theoretical analyses now available support the conclusion derived from engineering experience that heavier vehicles require thicker pavements, even though the intensity of load on the pavement

may be the same. For this case, increasing the pavement thickness in proportion to the square root of the load seems to be a reasonable criterion. For the case of heavy trucks using inflation pressures twice to three times those of passenger vehicles, the situation is correspondingly aggravated, and pavements definitely thicker than those indicated by the square root relation appear necessary.

This additional increase in thickness varies from a relatively small amount for stiff pavements to as much as 100% for very yielding pavements. The actual amount can be computed for any given case by application of the methods previously outlined, provided the characteristics of the pavement with regard to spreading of load can be evaluated.

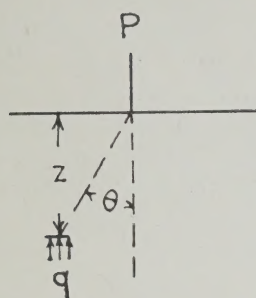


Fig. 1

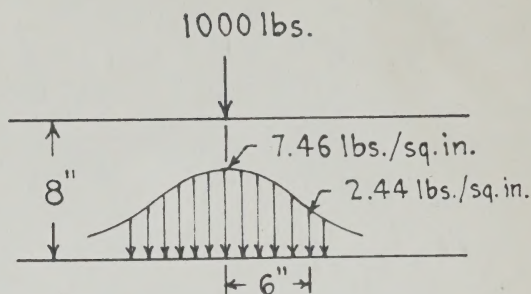


Fig. 2

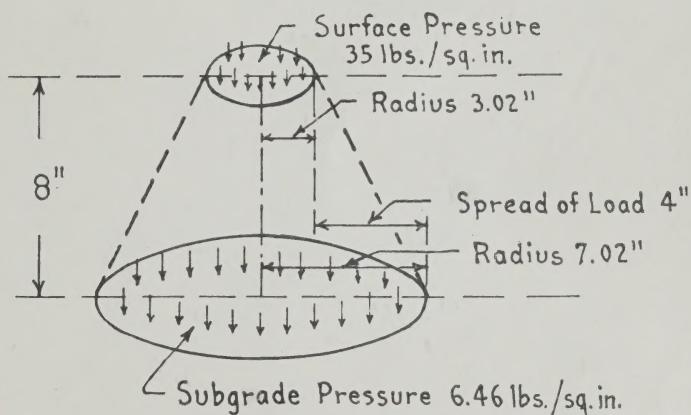


Fig. 3

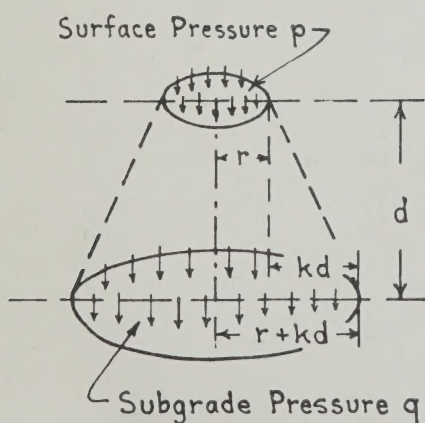


Fig. 4

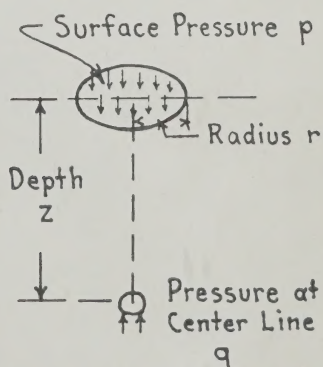


Fig. 5

